DESIGNING, DEVELOPMENT AND ASSESSMENT OF WIRELESS SENSOR NETWORK FOR CENTRAL MIXER SYSTEM TO CONSERVE WATER IN PUBLIC PLACES

BY

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To my beloved parents, sister, brother and nephew

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THESIS ABSTRACT

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TITLE OF STUDY: DESIGNING, DEVELOPMENT AND ASSESSMENT OF WIRELESS SENSOR NETWORK FOR CENTRAL MIXER SYSTEM TO CONSERVE WATER IN PUBLIC PLACES

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Water is the most valuable natural resource after air without which a man cannot survive. The growing demand is forcing fresh water beyond natural replenishment rates. This nictitates finding water conservation opportunities. We recognize that there is significant water wastage of cold water at public places as users try to find a proper setting of the mechanical water mixer. There is in need of a smart system that can handle the demand of water and simultaneously serve the users with water at a constant and comfortable temperature as well as regulated pressure. In this thesis, we propose a smart centralized water mixing system that provides water to users at a reasonable temperature and flow rate. This will help in eliminating *mechanical mixing and use of manual valves. The proposed system is designed using different sensors and controllers in such a way that it is easy to install and it also overcomes the drawbacks of the present system with enhanced features and proper quality of service. The conventional system and the proposed systems are simulated using the tools provide by Matlab. The obtained results show that with the integration of Wireless Sensor Network (WSN) and a control system with the conventional physical system, we can serve users with water at the desired temperature and flow rate. The proposed system provides significant water and energy conservation on top of improved quality of service to users.*

ملخص الرسالة

الاسم الكامل: محمد فايز الدين

عنوان الرسالة: تصميم وتطوير و تقييم من أجهزة الاستشعار اللاسلكية شبكة أجل مركزي نظام خلاطة للحفاظ على المياه في الأماكن العامة

التخصص: هندسة الكمبيوتر

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يعد الماء من أثمن الموارد الطبيعيه بعد الهواء والتي بدونها لا يستطيع الإنسان البقاء على قيد الحياة. الطلب المتزايد على المياه العذبة تجاوز معدلات التجديد الطبيعية. وهذا ما يدفع لإيجاد طرق للمحافظة على المياة. نحن ندرك أن هناك هدر كبير للمياة خصوصا للمياة الباردة في الأماكن العامة حيث يحاول المستخدمون إيجاد الإعداد السليم لخلاط المياه الميكانيكي. وهنا تبرز الحاجة إلى نظام ذكي والذي بإمكانة في آن واحد ان يتعامل مع طلب المياة و توفير للمستخدمين مياة بدرجة حرارة منتظمة و مريحة و كذلك المحافظة على ضغط منتظم.

في هذه الأطروحة، نقدم نظام مركزي ذكي لخلط المياه، والذي يوفر مياه للمستخدمين بدرجة حرارة ومعدل تدفق معقولين. مما سوف يساعد في القضاء على خلط واستخدام الصمامات اليدوية الميكانيكية.

تم تصميم النظام المقترح باستخدام أجهزة إستشعار وتحكم مختلفة وذلك بطريقة سهلة في التركيب، كما أنه يتوفر على الميزات المحسنة والجودة المناسبة من الخدمة ليتغلب على عيوب النظام الحالي .

تمت المحاكاة للنظام التقليدي والنظم المقترحة باستخدام الأدوات التي توفرها أظهرت النتائج التي تم الحصول عليها بأن تكامل شبكة الاستشعار اللاسلكية ونظام التحكم مع النظام الفيزيائي التقليدي، يمكننا من أن نوفر للمستخدمين المياة بدرجة الحرارة المطلوبة ومعدل التدفق المطلوب. كما ويوفر النظام المقترح الحفاظ بدرجة كبيرة على المياه والطاقة كأهم معالم تطوير جودة الخدمة للمستخدمين.

CHAPTER 1

INTRODUCTION

1.1 Water Conservation

Water is an essential resource for all the living things around the world. In the recent few decades there is a huge growth in the population [1] around the world and this rapid growth has created the shortage of fresh water. As the countries develop and populations grow, the demand for water is estimated to rise by 55 percent by 2050 [2]. By 2025, two thirds of the worlds population could be living in water-scarce countries if present water utilization patterns continue [3]. Around 40 percent of the worlds population lives in valleys that contain two or more countries, which account for about 60 percent of global fresh water flow with about 2 billion people worldwide dependent on groundwater [4]. Water supply catastrophe have been identified by government, academia, industry and civil society as one of the top three universal risks [5]. Adopting a water goal will send a clear message that policy makers should focus on this impending risk.

Among all the water scarce countries in the world, The Gulf Cooperation Council (GCC) countries face a serious water scarcity problem that threatens the continual development and interrupt the nationwide plans for agricultural, industrial and human development.

Saudi Arabia is a country that occupies about 85 percent of the Gulf Cooperation Council (GCC) area. It has no permanent surface water resources such as rivers or lakes and most of its area is covered with desert and very low rainfall rates. A considerable part of the clean water needs in the kingdom is desalinated water [6]. The shortage of clean water is one of the main challenges being faced by the people of kingdom. With the rapid growth in the countrys population by 43 percent in past two decade [7], there is a rapid increase in demand for clean water simultaneously there is also significant increase in water wastage in residential buildings and public restrooms. We find imperative to find opportunities for significant water conservation. Application of computer control and network to water systems can provide significant water savings.

In the recent years there have been a lot of advancements in the WSN technology, which has transformed the normal homes into smart homes. Sensing devices provide an essential technological infrastructure on top of which the smart home concept is built. A smart home is simply defined as a system that uses different advanced technologies to equip home appliances with intelligent monitoring capabilities such that the everyday home activities are automated without user intervention in a more efficient, safer and less expensive way. Sensor networks are being used in smart homes for water conservation [8]-[11]. This thesis is considered as an application of WSN to water conservation.

1.2 Wireless Sensor Network

A wireless sensor network (WSN) can be defined as a wireless network that consist of geographically disseminated independent sensors which are used to monitor environmental or physical conditions, such as light, pressure, temperature, location, etc. that serve as the basis for knowledge acquisition, management and decision-making. The data collected is passed through the network to the gateways that connect a wireless sensor with the rest of the world. In recent years, WSN technology has become increasingly advanced with the support of small, micro-mobile devices. It has gradually become a research hotspot for many researchers. A WSN deployment consists of few tens to thousands of sensor nodes that have the capability to monitor, store, process and broadcast the sensed data to a base station where further computation can be performed. The low cost and reduced operating expenses have made WSN more reliable, scalable and flexible to install. It also made numerous monitoring applications feasible that were previously not possible due to remote and hazardous environments. WSN has very extensive application prospects and high potential value in many areas, such as in the national defense and military [12]-[14], biomedical [15]- [17] and environmental monitoring [18, 19], industrial process monitoring and control [20], smart homes [21]-[25], etc.

1.3 Cyber physical system

A system where the physical process interacts with computational software and hardware is referred as Cyber Physical System (CPS). The hardware used is sensors and actuators, where the sensors collect data from the physical components and transmit this data in real time to the computational software in order to control the physical components. The cyber components analyses and process the data received from the sensors, it applies computational intelligence by using efficient algorithms to generate suitable control values for actuators to control the physical components of the system. The aim of CPS is to build an efficient, scalable and controllable physical system that will help in conserving the natural resources such as water, energy, etc.

In this thesis the CPS is applied to Water Distribution Network (WDN) in order to conserve water in public places. The traditional system of using water with mechanical mixers leads to lot of water wastage in the process of adjusting the mixer to get water at acceptable temperature. A simulation model of Centralized Water Mixing System (CWMS) has been proposed in order to solve this problem. The simulation method has been the most efficient solution for developing the actual physical system. It shortens the developing period of the physical system by pointing out the possible failures. It helps in the finding the suitable hardware and software that will not only improve the reliability and scalability of the system but also reduce the cost in building the actual system.

There are many water simulation tools such as EPANET [26], PIPEFLOW

[27] and SimHydraulics tool of Simulink [28] in the market that will help in the simulation of WDN. The hydraulic simulation tools have become powerful decision making-tools enabling the engineers and the scientist to analyze and manage the WDN with efficiency and accuracy. In this thesis we have used SimHydraulics simulation tool of Simulink to simulate the proposed CWMS. Simulink is an environment that can be used to design simulation models of multiple domains. It supports simulation, automatic code generation, system-level design and continuous test and verification of embedded systems. This software provides actual physical components such as pumps, valves, pipes, tanks and many more to simulate WDN. It helps in predicting the water behavior, calculating flows, pressures and heads, tank water levels.

1.4 Problem Statement

In modern restroom, each user's tap is equiped with a mechanical mixer to select a comfortable temperature and flow. In some buildings corner are cut and the hot line is not available. Despite the technological growth in water purification, water control is still very primitive causing significant wastage due to inconvenient adjustment of temperature and pressure. In some cases, accidental burning can happen to children as well as adults because of very hot water. In another aspect, it is seen from the daily experience that water is wasted in waiting rather in use in contexts similar to public restrooms.

Public places need more water to serve large number of users having different water usage habits; they use water according to their habit that leads to lot of water wastage. Due to manual control in the present system, the users forget to turn off the taps when they are not using the water. For example let us consider washing face, a simple day to day activity in every day life. During this simple activity, the user carries out many operations like: opening the tap, applying water on his face, going for soap, applying soap, cleaning the face with water and finally closing the tap. In this simple activity, few operations such as going for soap and applying it doesnt need water, but still the users leaves the water tap open for the whole time of activity. This simple activity shows that during half of the activity time the water is wasted by the user. If this simple activity is carried out by the large number of users at public places that will lead to significant amount of water wastage. This has to be changed using technological advancements. There is also a case where users waste water by letting it go till they receive water of desired temperature at taps, this problems and issues related to conventional system needs to be solved to stop water wastage and to avoid accidents in public places.

An ideal system is the one which provide water at correct temperature and flow rate and closes the tap when user is not actively using the water. The thesis goal is to design a system that approaches this idealized system behavior. We expect significant water and energy savings.

1.5 Thesis Outline

This thesis propose that Centralized Water Mixing System (CWMS) can be implemented to increase convenience and safety as well as significantly conserve water. There are several ways to implement this central mixing: fixed-ratio system and micro-controller based systems (smart). Smart CWMS is one solution that will overcome the issues related to fixed-ratio or what we call conventional CWMS. In this thesis, three smart CWMS have been proposed: Total Flow Temperature Control System (TFTCS) with variable speed pumps, total flow temperature control system with electronic valves and Temperature Control System (TCS) with one electronic valve. The proposed systems integrate the physical system with control system and wireless sensor network to solve the issues related to conventional system.

The systems designed is expected to save a considerable amount of water when deployed in real environments like public places such as airports, railway stations and hotels, etc. Smart CWMS is one solution that will overcome the issues related to conventional system. A layer of smart sensors will be installed on top of the physical system to provide feedback and control. TFTCS used sensors and Variable Frequency Drives (VFD) to control temperature and flow rate. TFTCS with electronic valves used temperature sensors, flow rate sensors and two electronic ball valves to control the mixing. TCS is the low cost version and used only one temperature sensor and one electronic valve. A controller has been designed to calculate the cold flow rate and hot flow rate based for the desired temperature at users. PID controller has been used to control the pumps and electronic valves based on the flow rate ratio provided by the designed mixer temperature controller. In TFTCS with variable speed pumps model instead of one pump on cold line two variable speed pumps that can change speed based on the mixer temperature controller input have been used. The proximity sensors and the solenoid valves installed at each tap helps in avoiding water wastage. The proposed systems have been simulated using the physical modeling tools provided by MATLAB [28]. Our contribution can be summarized as follows:

1. Designing a smart centralized water mixing system that incorporate the WSN and control system.

2. Building a simulation model of the proposed smart centralized water mixing system and

3. Study the effect of different Quality of Service (QoS) constraints like temperature, flow rates and pressure under realistic conditions.

1.6 Summary

This thesis presents a novel system in the area of centralized water mixing that helps to conserve water in public places and improve user's QoS. Different optimal solutions are considered for achieving certain objectives under various QoS constraints. The rest of the work is organized as follows, a detailed literature review in this area is provided in Chapter 2. Chapter 3 provides detailed information about the system design. The simulation model is discussed in the Chapter 4. Chapter 5 describes the results obtained from the simulation. Conclusions and future work are discussed in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

A WSN consists of small, energy constrained sensors, which are used to monitor various events and report back to Base Station (BS). There is a growing body of work done in the field of WSNs to conserve water. The evolution WSNs have led to a cost effective realization to solving such problems. In the recent times many researchers have integrated the WSNs with the Water Distribution Network (WDN) to monitor the water flow, to find the ruptures in the pipes to avoid water leakage and to conserve water in homes and public places. In this section we present the current works in which the researchers have used WSNs to solve the problems related to water.

Water conservation programs targeted at large users in the urban areas play an integrated role in reducing the water consumption and wastage. It not only contributes in securing water for individual homes but also in acquiring whole area water supply. According to authors in [11] the water usage can be minimized only when we get a proper knowledge about the water use at a particular site.

They suggested that by integrating appropriate water management system with the physical system will give an integrated water conservation scheme that will minimize the wastage of water.

The researchers consider that WSN is one such technology that has emerged over the time in the field of water management system due to recent advancement in sensor, electronics and wireless communication technologies. The authors in [29] presented the challenges faced by the wired based communication system in monitoring the water pipelines. They suggested that WSN technology will overcome the challenges faced by wired communication system. A WSN can be easily deployed in a large field to continuously monitor the events without human intervention. They presented the recent works done in the area of water pipeline monitoring using WSN technology for different scenarios such as underwater, underground and aboveground. Building a smart and efficient WSN for water management system is always a tough task due to many challenges. Some of the challenges are discussed in [30].

According to authors in [30], long network lifetime, network resiliency to natural or manmade disasters and cost of the sensor network are some challenges that are being faced in building WSN for water management system. They suggested some attributes that an ideal WSN should have. The attributes are: multiple levels of QoS, scalable, resilient, fault tolerant and cost effective. To address the above mentioned challenges they proposed a decentralized single-hop architectural framework called AQUA-NET. Our work is to design and build a smart CWMS system for water management system to conserve water in public places. We will acquire the attributes for an ideal WSN presented in [30]. The physical systems proposed in [31] and [9] are a bit close to our work.

Hot water DJ proposed in [31] is a fixture and water flow monitoring system that provides hot water at different temperatures for each fixture based on the requirement. It was designed to save the water heater energy and minimize the energy wastage due to pipe loss. Their proposed system consists of pressure sensors, water flow sensors, hot water tank and a mixer that is installed near to the hot water heater. The mixer issued to mix both hot and cold water running out of the pipes in a proper ratio so that the user receives the water of the desired temperature. The authors conducted experiments in a test home environment for almost six days and compared the performance of the proposed system with the present standard water heater. The results show that they were able to save 10 percent of water heater energy using the proposed system. The work we propose is similar to Hot Water DJ in terms of using water mixer. However, the mixed water is the final mix at serving temperature and it is consumed by large number of users in public places such as airports, or road stations where you encounter large number of users. In our work we aim to provide constant flow rate along with water at constant temperature for large number of users. Many intelligent systems have been proposed in the recent times for water monitoring using WSN. The integration of the WSN technology and Information Technology (IT) with physical systems has been a major breakthrough in the recent times. This has enabled previously unattainable tasks.

A vibration-based water flow monitoring system was developed and evaluated in [9]. In the earlier work [10], the authors proved the feasibility of vibration sensors in water flow monitoring by deploying and evaluating in a lab setup. In [9], they deployed the system in existing environment and performed a detail study of performance aspects such as sensing sensitivity and stability, model appropriateness and adaptability of system. They also discussed real threats and experiences from the extensive deployment and suggested that estimated water utilization information could provide important information to the users, which will help in saving water. In our work, we aim to provide users with in detail information about the consumption of hot water and cold water over a period of time using water flow meters.

B.panindra et al. proposed a Wireless Sensor Network (WSN) based intelligent monitoring system that can be used to monitor the overhead tanks in [32]. The proposed system controls the pumping of water into the water tanks based on the level of water in the tanks. The objective was to detect the scarcity of water and also to control the distribution based on available water source. The system is composed of a WSN coordinator node that monitors overhead tanks and remote nodes that are attached to the overhead tanks. ZigBee wireless communication protocol was used to transmit data from remote node to coordinator nodes. Every overhead tank has one fixed remote node that has a level sensor to measure the level of water, a ZigBee module for communication purpose, a motor pump for pumping water into the tank and a microcontroller that will control the remote node. Proteus Integrated Development Environment was used to simulate the proposed prototype; a three tank model with three level sensors and three motors was simulated to test the proposed monitoring and distribution system. A minimum level of 25 percent and maximum level of 75 percent of the capacity of tank was fixed to switch on and switch off the motors respectively. In our work we aim to use pumps along with variable frequency drives that will control the pump speeds. A wide variety of sensors like water flow sensor, proximity sensor, pressure sensor and temperature sensor will be integrated to make the system efficient.

Many researchers have used CPS as the tool to solve the issues related to WDNs. It is simply defined as integration of computation with physical systems and physical processes in [33]. In this section we will discuss some of the works in which the researchers have modeled CPS in [34]-[37], and used simulation tools in [38]-[41] to solve the issues related to WDN.

According to the authors in [34] there are very limited tools available for modeling and simulation of CPS. They used present domain-specific simulation tool EPANET and MATLAB to simulate the CPS for WDN. They presented the challenges in simulation of CPS. One of the challenges is the lack of exact and specific representation of the properties and operation of the physical infrastructure. In our work we used SimHydraulics tool of MATLAB to simulate CPS, which gives more accurate and precise representation compared to EPANET. In [35], the authors have presented the applications of Mobile Adhoc Network (MANET) and Wireless Sensor Network (WSN) and how they drive the progress of CPS. The result of survey show that WSN focusses more on the sensing, event-handling, communication, and data-retrieving issues, whereas the CPS focusses more on the development of cross-domain intelligence from different WSNs and the communication between the physical world and the virtual world. In [36], an agent-based modeling for WDN as a case study of CPSs was presented. The agent was defined as an individual entity that maintains resources within its local scope such as sensors, actuators and physical processes. Similarly in [37], an agent based approach is proposed for linking the physical and cyber layers. The physical components used are valves, pumps pipes and the cyber components are sensors, communication lines and operator work stations. The data from the physical components is extracted by the sensors and communicated through the transmission lines to the operator workstation. In our work similar kind of physical components were used, but the communication is not wired, its wireless. The proposed model was helpful for designing the CPS for CWMS.

The authors in [38] presented a simulation model for water resource cycle that will help in water resource management as well as water disaster countermeasures. The tool used is GETFLOWS developed by graduate school of engineering, university of Tokyo. One more tool that is popular in WDN is EPANET. The authors in [39] used EPANET tool to simulate the water supply network of Hengshanqiao town. Many researchers have also used real time data of WDN into simulation model to analyze the behavior of the physical system. In [40] order to make real-time simulation of WDN, the real-time data such as flow rate, pressure, head of reservoir and pump information was collected every 15 minutes. This data was sent and received in to WDN using object linking and Embedding for process control communication of Supervisory control and data acquisition system. EPANET was also used in 2009ecabrera2009 along with SWMM simulation software to model initial network charging and roof tanks for intermittent WDN.

CHAPTER 3

PHYSICAL SYSTEM DESIGN

In this section the design and operation of the fixed-ratio system and three newly proposed systems are presented. The advantages and disadvantages of each system will be discussed.

3.1 Overview of cyber physical system

The complete design of the cyber physical system can be explained using Fig. 3.1. The system is conceptually divided into three sub-systems: physical system, control system and wireless sensor network. The physical system is the water supply system that comprises water tanks, pipes, pumps, valves and taps, etc. The control system includes the controllers designed to control the temperature and the flow rates serving at the users. The wireless sensor network is the system deals with all the sensors that need to be mounted on the physical system. The sensors provide the behavior of the physical system to the control system as well as to the users via internet or any local area network.

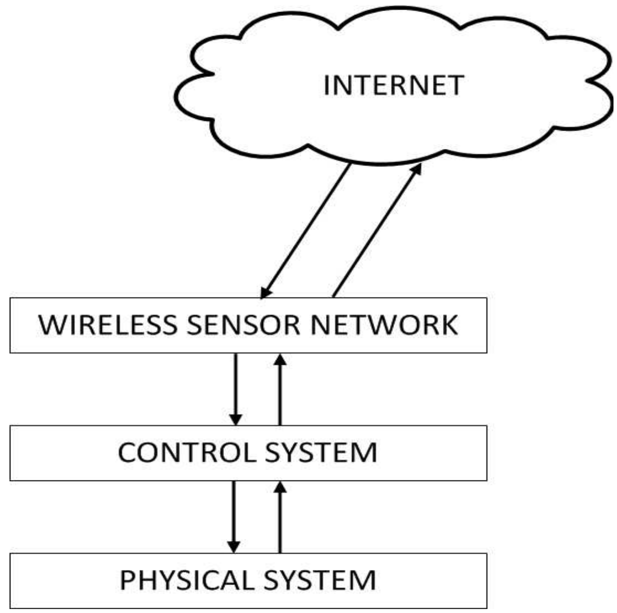

Figure 3.1: cyber physical system overview

3.2 Fixed-ratio mixing system

In this section the design and the operation of the fixed mixing ratio system is presented which is very cheap to implement and requires no micro-controller. The user can simply set the mixing ratio in the morning and leave it at that setting for the remainder of the day. Fig. 3.2 gives an overview of the system; it has a pump that is used to pump water from cold tank to the heater and to the mixer. The hot water from the heater gets mixed up with the cold water coming from the cold tank in the mixer in the ratio set by the user manually. This water at some unknown temperature is served to the users arriving randomly at the taps. In this system, the users receive water at different temperatures and flow rates. The temperature of water at users is dependent on the temperature of water in the heater; if it is at high temperature then hot water is served or else vice versa. To avoid this wastage of water, three smart CWMS have been proposed: TFTCS with variable speed pumps, TFTCS with electronic valves and TCS with single valve as shown in Fig. 3.3, Fig. 3.4 and Fig.3.5 respectively.

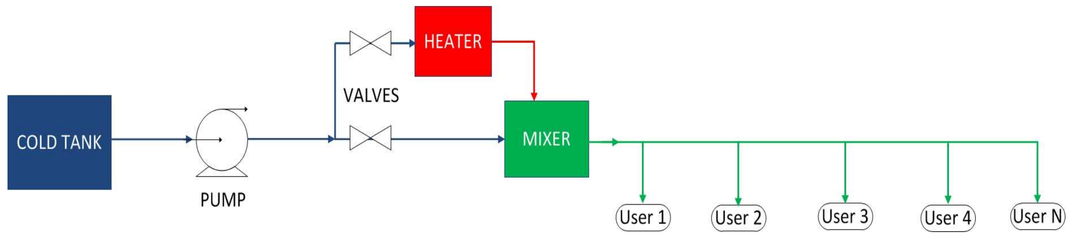

Figure 3.2: Fixed-ratio system

3.3 Total flow and temperature control system with variable speed pumps

It is evident from daily life that the users leave the tap open whole time even if they are not using the water. There are OFF times during the usage where users do not use water, like when they are applying soap or adjusting the clothes, etc. It is very important to stop water wastage in OFF times during usage of taps. To solve this issue, TFTCS has been proposed. TFTCS as shown in Fig. 3.3 handles both temperature control and flow rate control along with OFF times at water taps. The system uses proximity sensors to differentiate between OFF time and ON time during the tap usage. The proximity sensor is installed under the tap and only when the user comes close to tap, the water is served. Solenoid valves installed at each tap and they open only when they receive signal from proximity sensor. This way the water is served only during ON times when user is actually using the water. TFTCS has two pumps unlike fixed-ratio and temperature control system that work with only one pump.

The two pumps are connected to Variable Frequency Drives (VFD) that will control the speed of pumps in either direction. The total water demand at taps is calculated based on the user arrivals. Proximity sensors installed at each tap will help to calculate the total taps open at each point of time. The required flow rate at each tap multiplied by the number of taps open will give the total flow rate. After calculating the required flow rate, the next step is to obtain the ratio of hot and cold flow rates to get water at a desired temperature at mixer. This task is done by Mixer Temperature Controller (MTC) that will calculate the ratios and send signal to the variable frequency drives to pump the desired flow rates. In this system there is lot of data dissemination from the sensors to the controllers designed. Fig. 3.4 present one more version of TFTCS where VFDs and two pumps replaced by two electronic ball valves and one pump. In this design the controller control the ball valves to serve the users with water of comfortable temperature and pressure. TFTCS has many advantages over the conventional system; some of them are listed below:

1. Water is thermally stabilized.

2. Child/user safety.

3. Reduced wasting due to user manual control.

4. Regulated temperature also saves water in trying to adjust /readjust water.

5. Automation reduces maintenance cost and reduces user-misuse of manual

apparatus.

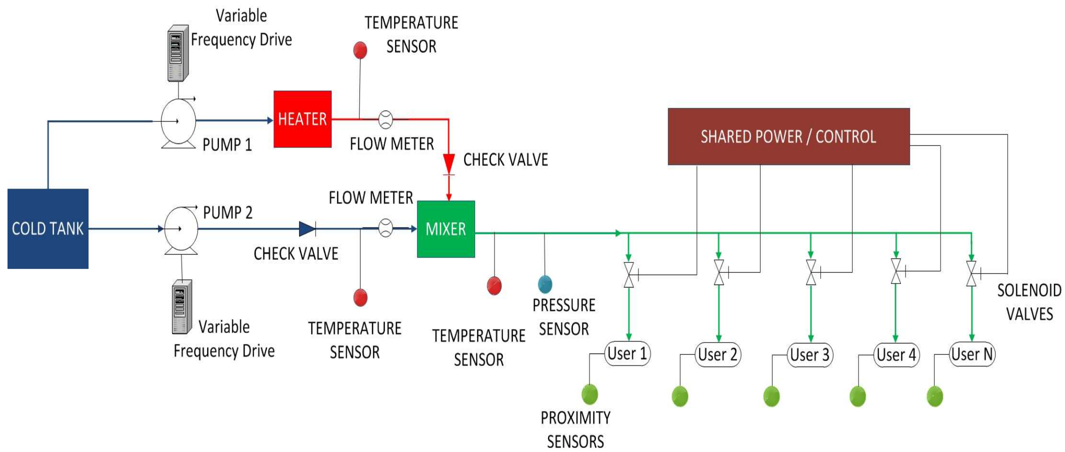

Figure 3.3: Total flow and temperature control system with variable speed pumps

3.4 Total flow temperature control system with electronic valves

One more system that can be used to solve the issue of proper mixing of hot water and cold water is shown in Fig. 3.4. In this system, the physical system is integrated with control system and wireless sensor network. TFTCS with electronic valves uses electronic ball valves replacing the two VFDs and two pumps with single pump to control the mixing. The temperature sensors provide the exact temperatures of water coming out from heater, cold tank and the mixer. The flow meters mounted on the cold and hot pipes gives the flow rates of hot and cold water respectively and the proximity sensors installed at users provide the total flow demanded by the users. Wireless Sensor Network is used to update the controller with the temperature sensors and proximity sensors data at each point time. A controller has been designed to calculate the cold flow rate and hot flow rate based on the desired temperature at users and the readings available from the temperature sensors and proximity sensors. The controller also controls the openings of the electronic ball valve on both pipes to release the desired flow in to mixer. The check valve installed on hot and cold pipes help in avoiding negative flow. In this way the system tries to provide the users with a water of desired temperature. If the temperature of the heater falls below the desired temperature, the water is served from heater and the ball valve on the cold pipe is closed. The detailed working of the designed controller will be discussed in the simulation part. The advantage of this system is that the users will be served with water of desired temperature and pressure. The system presented in Fig. 3.5 is the simplified version of TFTCS with no proximity sensors and only one electronic ball valve before the heater and temperature sensor after the mixer. The valve is controlled based on the temperature at mixer. This system is very simple and lower cost version and considered as only temperature control system.

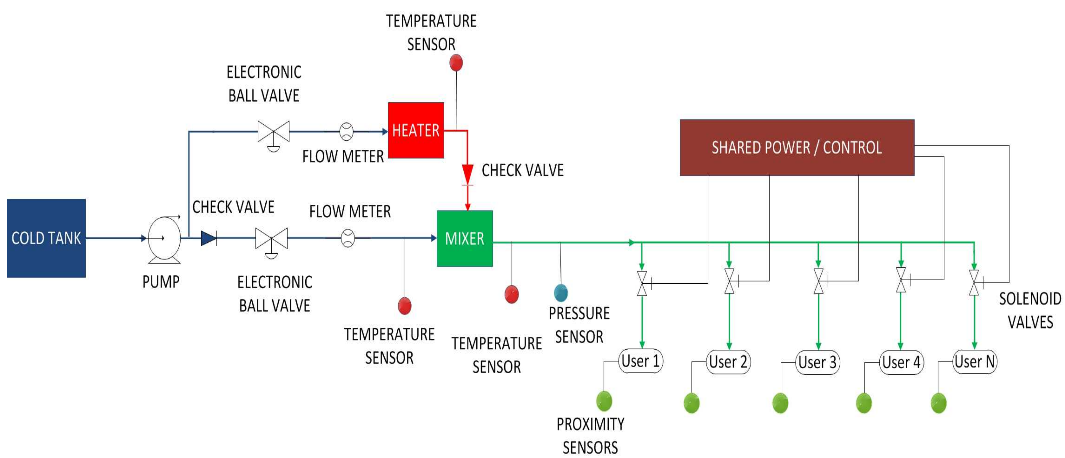

Figure 3.4: Total flow temperature control system with electronic valves and a single pump

3.5 Temperature control system with electronic valve

The system presented in Fig. 3.5 is the simplified version of TFTCS with no proximity sensors with only one electronic ball valve before the heater and temperature sensor after the mixer. The valve is controlled based on the temperature at mixer. This system is very simple and lower cost version and considered as only Temperature Control System (TCS). In this system the controller generates the electronic valve signal based on the temperature of water after mixer. The valve orifice is increased to release more hot water if the temperature of the water after the mixer is less than the desired temperature and vice versa. A gate valve is installed on the cold line to decrease the pressure of the cold water in order to properly mix the water in mixer. If there is no gate valve on the cold line then the pressure on the cold line will be more compared to hot line that will stop water coming out from the valve. In order to successfully functioning of this system, the pressure on the cold line should be less the pressure on the hot line.

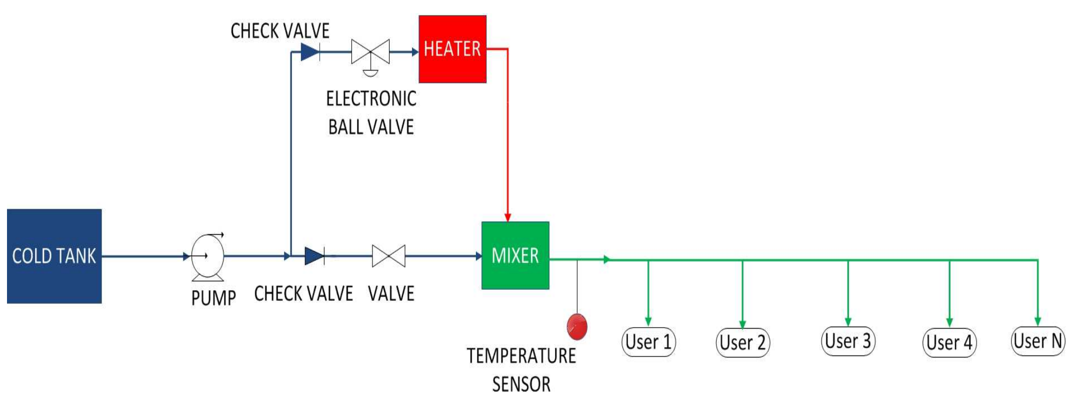

Figure 3.5: Temperature control system with electronic valve

CHAPTER 4

SIMULATION

The four CPSs designed in the previous section have been implemented using Simulink and physical modeling tool SimHydraulics with new features introduced in 2014 provided by MATLAB [28]. Simulink is an environment that can be used to design simulation models of multiple domains. Simulink supports modeling and simulation of dynamic systems of multiple domains, automatic code generation, system-level design and continuous test and verification of embedded systems.

It has a user friendly graphical editor, solvers for modeling and simulating dynamic systems and customizable block libraries. It is combined with MATLAB, enabling the users to integrate MATLAB algorithms into models and export the results obtained from simulation to MATLAB for detailed analysis. It contains libraries that help in modeling continuous-time and discrete-time systems. The simulation results can be viewed using scopes and data displays.

SimHydraulics is physical modeling software that gives us different ways to simulate and evaluate hydraulic power and control systems in the Simulink environment. It includes models of hydraulic components, such as pumps, valves, pipelines, actuators, and hydraulic resistances. These components can be used to model fuel supply and water supply systems. The models developed in SimHydraulics can be used to develop control systems and test system-level performance. The models can be parameterized using MATLAB variables and expressions.

4.1 User arrivals and service time

To test the four systems in a real world scenario, random user arrivals are generated with random service time at each tap over a period of three hours. The user arrivals are less in the first hour and increase exponentially in the second and third hour. Service time is defined as the total time that a user leaves the tap open. A Matlab code is written to generate random user arrivals having different service times ranging from 30 seconds to 180 seconds. During service time there are ON and OFF times that should be considered in TFTCS.

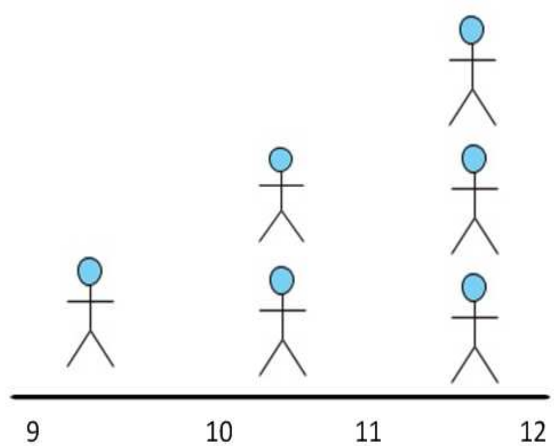

Figure 4.1: User arrivals

In [42] the authors examined the tap usage using water sound analysis, they categorized the water waste into two types: Intra-activity waste and Inter-activity waste. Inter-activity waste occurs when the water flow and there is no activity taking place at the tap, in this case the user might have forgot to close the water tap after utilization. The other waste is Intra-activity waste that occurs during the activity at the water tap like when brushing your teeth; the user opens the tap and goes to get toothpaste hence getting toothpaste can be treated as a wasteful activity if the water tap is still open. This time is defined as OFF time and the time when the user is using water is defined as ON time. To calculate ON and OFF time during service time, experiments have been conducted.

The experiments have been performed in a university washroom with real user. Two stop watches have been used to keep track of ON and OFF times during the service time. In the first experiment, the user has performed simple activity of washing his hands. In this activity he followed the steps that any normal user does it. The steps are: opening the tap, wetting the hands, going for hand wash, applying hand wash and washing hands. In this activity the actions "going for hand wash and", "applying hand wash" are considered as OFF times. The stop watch readings show that 40 percent of service time is the OFF time. In the second experiment the user performed washing of face, hands and legs. In this activity, the results obtained show that 60 percent of service time is the OFF time. TFTCS service time has been integrated with the ON and OFF times to show how the usage of proximity sensors at the taps will help in conserving water.

4.2 Heater temperature dynamics

This model assumes that the heater volume is sufficiently large and the flow rates sufficiently small in comparison, so that the hot water output flow is perfectly balanced by the cold water input flow for replenishment, hence maintaining constant volume. It also assumes that there are no heat losses from the heater to the environment. Additionally, the heat exchange processes in the volume are instantaneous, and therefore the temperature in the volume is homogeneous. The heating source is constant and ideal with a heating rate of 0.2 Degrees Celsius per minute obtained from volume of heater (200 liters) and power (3KW). The heating element is switched on as soon as the temperature descends below a small threshold of 0.5 Degrees Celsius from the maximum heater temperature of 70 Degrees celsius, and stays on until the target temperature is reached again. The model has been obtained through the following derivation.

$$T_f = (T_h(V_h - V) + T_C V)/V_H \tag{4.1}$$

The first equation is the formula for the final temperature of two volumes of liquid that come in contact. It is based on the principle of energy conservation. The hot volume V_h is reduced by an output volume V, but compensated by an input volume of equal amount. T_h, T_c are the temperatures of hot and cold water and T_f is their final temperature. However, a differential equation is needed for

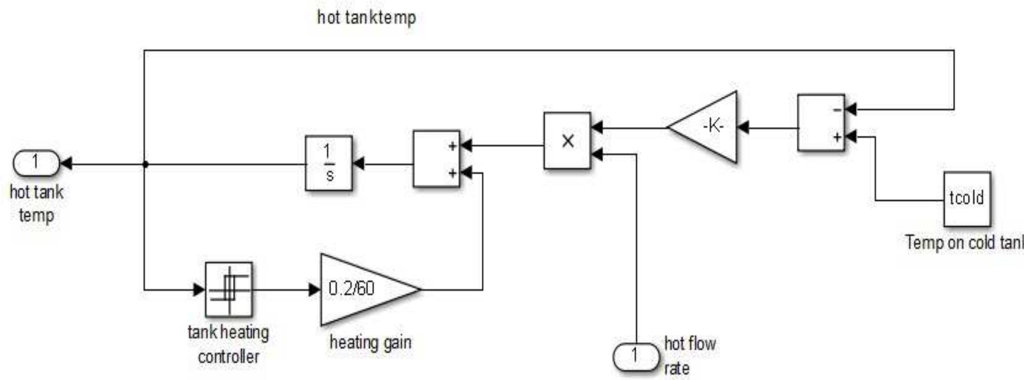

Figure 4.2: Hot tank temperature dynamics

a continuous time simulation in Simulink, and is therefore needed to differentiate with respect to time and is therefore needed to differentiate with respect to time and solve for dT_f/dt.

(-dV/dt)$T_h - V_h(dT_f/dt) = (-dV/dt)T_c$

d$T_f/dt = ((T_c - T_h)dV/dt)/V_h$

Finally, the heating component has been implemented as a constant input into the temperature time derivative and on/off state is controlled with a relay block.

4.3 Mixer temperature dynamics

The subsystem designed to model the behavior of an ideal mixer, where the outflow is always equal to the inflow, hence displaying constant volume in the chamber. Note that its dynamics are identical to that of the heater temperature dynamics, with the following differences. First, no heating is present. Second, the temperature of the input flow is the one given by the instantaneous hot and cold flow ratio. Third and last, the volume is different and much smaller. In the end, this subsystem provides a better representation of the temperature of the water flowing out of the taps, since it adds the inertia dynamics present in a real system.

4.4 Mixer temperature controller

This controller computes the flow mix ratio to achieve the desired T_{mix} and and subsequently outputs electronic valve signal in case of TFTCS with electronic valves, and the pump speed correction in case of TFTCS with variable speed pumps. The hot and cold flow ratios are calculated using the following equations.

Cold flow + Hot flow = Total flow

$$F_c + F_h = F_t \tag{4.2}$$

According to heat balance equation:

Heat gained by cold water = Heat lost by hot water

$$F_c(T_{mix} - T_c) = F_h(T_h - T_{mix}) \tag{4.3}$$

$$F_c * T_{mix} - F_c * T_c = F_h * T_h - F_h * T_{mix} \tag{4.4}$$

$$F_c * T_{mix} + F_h * T_{mix} = F_h * T_h + F_c * T_c \tag{4.5}$$

Solving the equation for T_{mix} we get

$$T_{mix} = \frac{F_h * T_h + F_c * T_c}{F_c + F_h} \tag{4.6}$$

$$T_{mix} = \frac{F_h * T_h + F_c * T_c}{F_t} \tag{4.7}$$

Substitute the value of F_h=F_t-F_c from equation 4.2 in the above equation

$$T_{mix} = \frac{(F_t - F_c) * T_h + F_c * T_c}{F_t} \tag{4.8}$$

$$F_c = \frac{F_t * (T_{mix} - T_h)}{(T_c - T_h)} \tag{4.9}$$

$$F_h = F_t - F_c \tag{4.10}$$

4.5 Tap system

The tap system has been modeled using many physical blocks such as resistive pipes, tanks, ball valves, flow rate sensors, scopes and displays as shown in Fig. 4.4. Each physical block used will be discussed in detail in the following sub sections.

4.5.1 Constant head tank

The tank modeled is initially empty tank that can accept an infinite amount of volume maintaining a constant pressure. The size of the tank is considered to be huge enough to ignore the water level change and pressurization. The tank

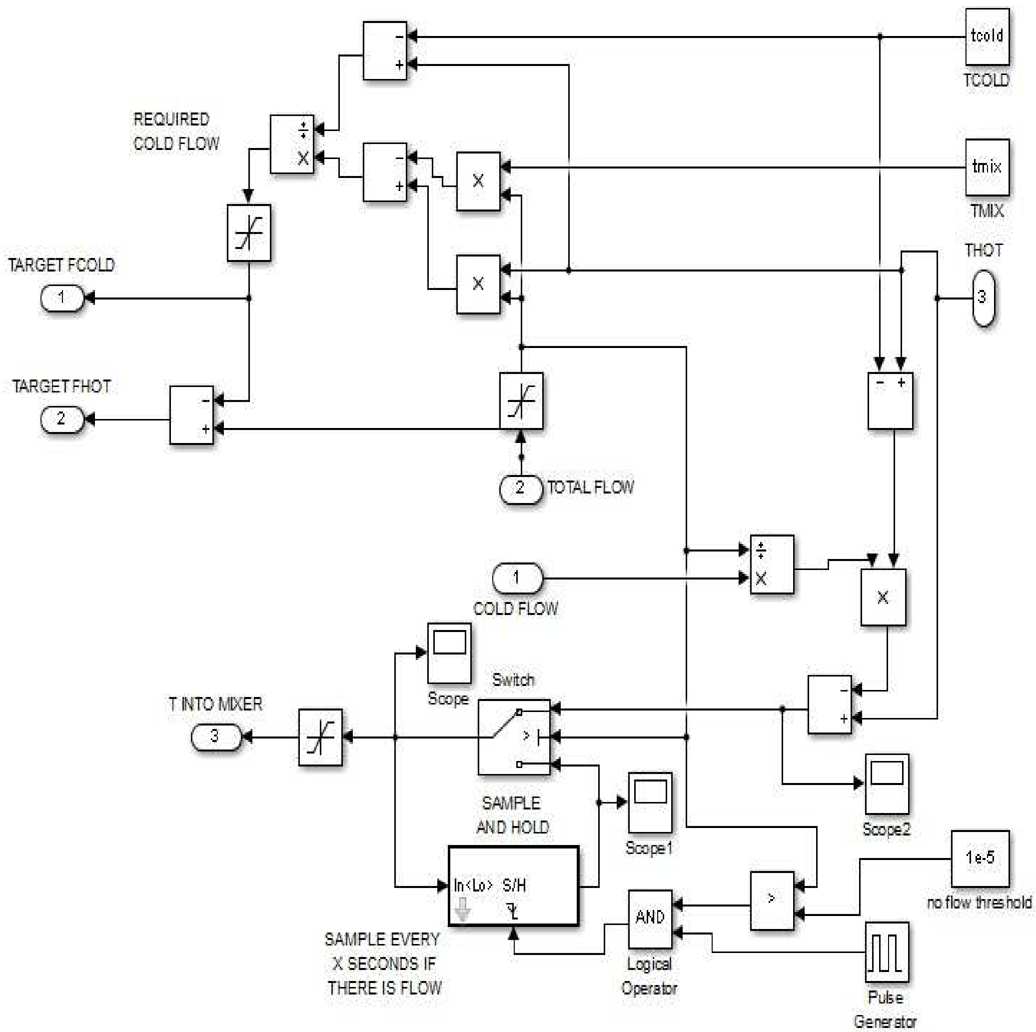

Figure 4.3: Mixer temperature controller

accounts for the water level elevation considering the tank bottom and the pressure lose in the pipes connected. The pressure loss can be caused by a filter or some other local resistances and it is specified with the pressure loss coefficient. There are two ports: V is a physical signal port and T is a hydraulic port related with the tank inlet. The volume of water in the tank is computed and exported outside through the port V. The flow rate is assumed positive if the water flows from the tank.

4.5.2 Ball valve

The flow control is modeled by a ball valve of a maximum aperture diameter of 5mm, similarly to one found on any normal installation. The valve is controlled by the corresponding user arrival signal given to the physical signal port S. There are two hydraulic ports A and B related with the valve inlet and outlet respectively. The water flows from port A to port B.

4.5.3 Resistive low pressure pipe

Some hydraulic circuit resistance has been implemented using a resistive low-pressure pipe with reasonable values for the model. This block represent hydraulic pipe with both circular and noncircular cross sections. It has two hydraulic ports A and B with positive direction from port A to port B. It is used in simulations that has low-pressure systems and, for this reason, requires specifying the elevation of both ports. The block not only can be used as a pipe itself, but also combination of pipes and local resistances such as fittings, bends, etc., associated with the pipe. The flow rate is considered positive if water flow from A to B.

4.5.4 Hydraulic flow rate sensor

Hydraulic flow rate sensor performs as an ideal flow meter, that is, a device that converts volumetric flow rate through a hydraulic line into a control signal proportional to this flow rate. The connections A and B are conserving hydraulic ports connecting the sensor to the hydraulic line. Connection Q is a physical signal port that outputs the flow rate value. The sensor positive direction is from port A to port B.

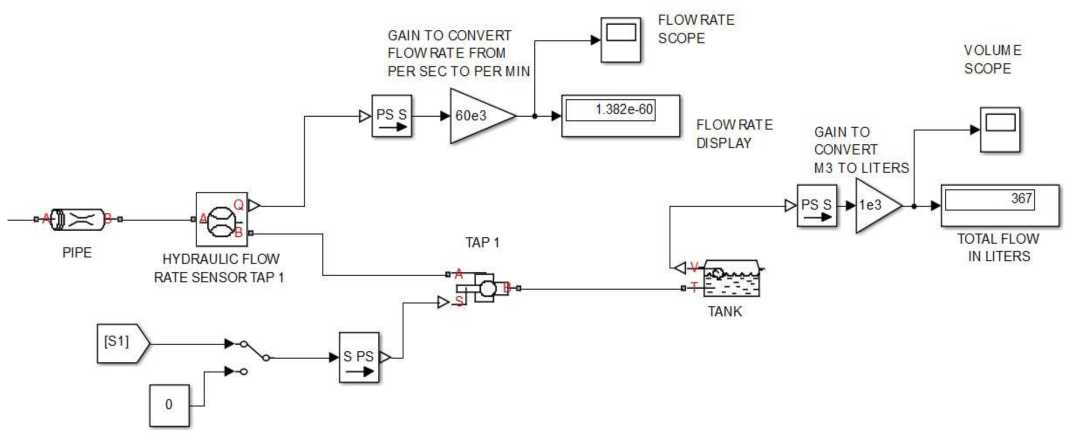

Figure 4.4: Tap system

4.6 Fixed-ratio mixing system simulation

The fixed-ratio mixing system is implemented as shown in Fig. 3.2. It has one cold tank that outputs a cold water of temperature 15 Degrees Celsius, a heater and a mixer with the above mentioned temperature dynamics respectively. The pump used is a centrifugal pump with single inlet and outlet as shown in Fig. 4.5. The ports T and P are hydraulic ports related with pump inlet and outlet respectively and the third port S is a mechanical rotational port related with the pump driving shaft connected to angular velocity source. If the shaft S rotates in positive direction then the pump transports fluid from T to P. The port T of pump is connected to a cold water tank with large capacity. The cold line from port P forks into two lines: cold line and another line that feeds the heater. The ideal angular velocity source block connected to the port S of pump is used to generate the mechanical rotation, it introduces a velocity differential at its terminals corresponding to the physical input signal. It has three ports, R and C are mechanical rotational ports and S is the physical port through which the control signal that runs the source is applied. The source is considered ideal in a sense that it is assumed to be dynamic enough to provide specified velocity regardless of the torque applied on the system. The port S is set to 650 radians per minute (rpm); it is set using trial and error based on the resistances of pipes, valves and taps to deliver water at an average flow rate of 5 liter per minute (lpm) at each tap.

Hydraulic Fluid block is used to assign the working fluid for all components assembled in a particular loop. The loop detection is performed automatically and the block is considered as part of the loop if it is hydraulically connected to at least one of the loop components. The block offers wide selection of fluids to choose from. The custom fluid is assigned with the Custom Hydraulic Fluid block from the Simscape foundation library. If neither Hydraulic Fluid nor Custom Hydraulic Fluid block is connected to the loop, the default properties of the Custom Hydraulic Fluid block are assigned.

Solver configuration block is used to define solver settings for the simulation model. Every Simulink model needs to have a solver block; in our model we are using the solver block with default settings. The simulation time is 3 hours where users arrive at the taps randomly. The results obtained during simulation are captured using the scope block in Simulink.

4.7 Total flow and temperature control system simulation with variable speed pumps

The proposed system is implemented using the same physical components such as pumps, pipes, valves and taps that are used in the conventional system. Instead of one pump on cold line we are using two variable speed pumps that can change speed based on the MTC input. The specifications are that the system has to provide approximately 5 lpm to each user that is arriving at the taps. Two pumps must provide the total flow demanded at each point in time and also control the hot and cold flow rates separately in order to provide water at a specified temperature T_{mix}. The variables to control are therefore two, the total flow, and the flow ratio. The ratio calculation is based on an energy balance between hot and cold flows

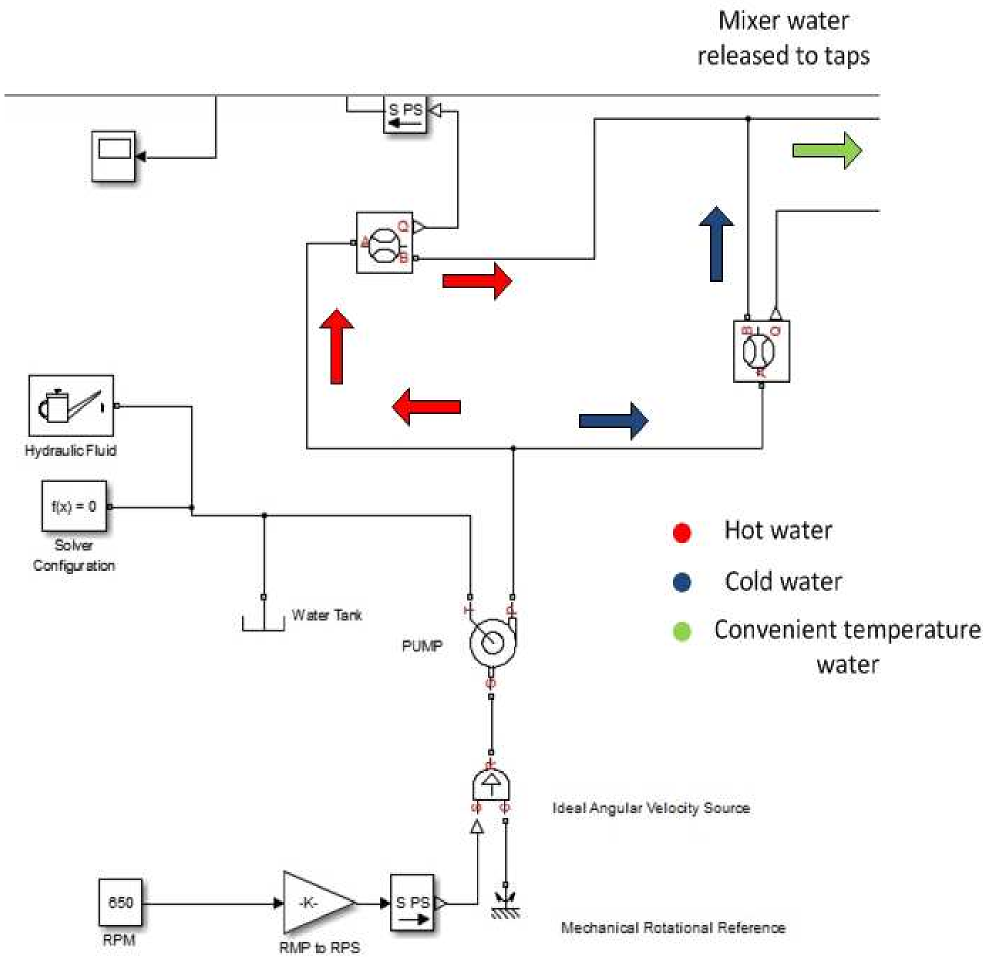

Figure 4.5: Fixed-ratio system model

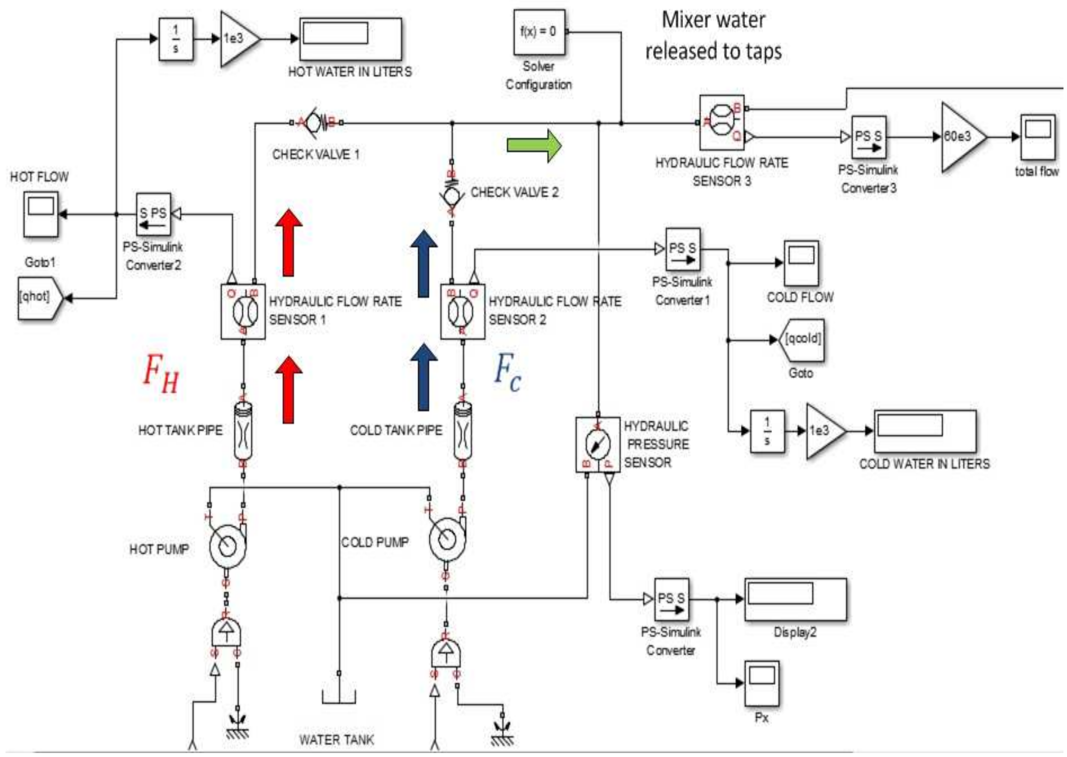

Figure 4.6: TFTCS with variable speed pumps model

and temperatures. The total flow is known by means of the proximity sensors at each tap. The system should consider the ON and OFF times during the service time at the taps.

The system is actuated by means of two pumps that can run at different speeds. The total flow they generate among them is inevitably the flow being sent through the pipes to each tap. Therefore the first task of the controller is to vary the speed of the pumps as a whole, so that the total flow adapts to the requirements, which change over time as taps are open and closed. See the next example for clarification. If one tap opens suddenly, the outflow through each tap will instantly decrease. The total flow controller will then react to that change and begin compensating by increasing the speed of both pumps until the total

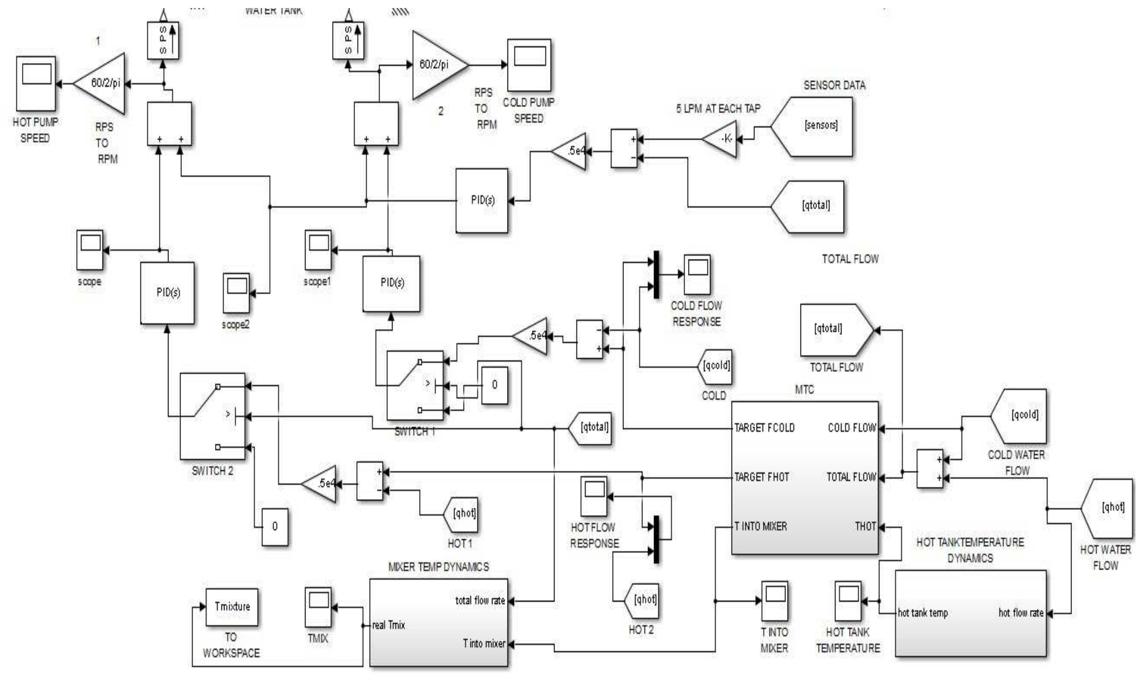

Figure 4.7: TFTCS with variable speed pumps control model

flow is again equal to the number of open taps times 5 lpm.

The second control problem is the flow mixing ratio system. The basic idea here is to think that, since the total flow needs to be independent of the desired T_{mix} temperature, it will be necessary to vary the speed of the pumps in different directions. In other words, when one increases the other will decrease and the other way around, so that the required total flow is maintained.

Note that after realizing this concepts for designing the control, it is important to test whether both requirements can be met simultaneously, which is not always possible. Testing whether the control problem can actually be separated in smaller control problems is also recommended for the same reason. Thankfully, in this case both requirements are met and the control can be divided into two parts: Total Flow Controller (TFC) and Mixer temperature controller discussed in previous section. Both are summed together to solve the problem.

Total flow controller is quite simple, the total flow is subtracted from the reference value that it has to follow, which is 5 lpm times the number of taps open at that point of time. The opening and closing signal of taps is provided by the proximity sensor attached to the taps. The controller assumes that the signals from proximity sensors have a value of 0 for negative detection, and 1 for positive detection. So that if two are ON, for example, the reference flow is 10 lpm. Next, the error signal (5*(sum of sensors signal)F_T) is multiplied by a gain of $0.5e^{-4}$. Its actual value is not extremely important; since its function is to more or less convert from very small m^3/s (of the order 10^{-4} to a range of values closer to the pump speed rotation in radians per second (rps) (of the order 10^3). Finding this value is rather experimental.

The total flow demanded is provided to MTC to generate the mixing ratio of hot and cold water to get desired temperature. The MTC controller computes the flow mix ratio to achieve the desired T_{mix} and subsequently outputs the pump speed correction that is applied to the signal coming from the TFC controller as shown in Fig.4.7. The image is better read from right to left, starting with q_{hot} and q_{cold}, the hot and cold flow rates respectively. Next is the mixing computation subsystem, which calculates the required values of the flow rates to generate T_{mix}. The target flow ratios coming out from the aforementioned subsystem are compared with their respective actual flow ratio. Then, that value is converted with a gain. After that, a switch block is found. This block prevents strange behaviors of the controller when the flows are zero. It is setup so that it will select the zero signal when the total flow is below an arbitrary threshold $1e^{-5}$, meaning zero flow. Then there is the PID block, which is the same for both branches, and is configured so that the response is sufficiently good as well as the stability. These values have been found by trial and error since no precise performance values have been specified. Finally, the signals coming out from the PID blocks are fed into their respective addition blocks, and as said before, will correct the common speed value of the pumps that has been computed with the other controller.

In our model only PI has been used. Effectively, the integral part increases the output signal when the difference between the actual value and the desired value of the control variable is positive, decreases when its negative, and is zero otherwise. The PID has a higher integral part than proportional part. This makes it react faster to perturbations, but such perturbations are also larger due to the smaller proportional value. To calculate the hot and cold flow ratios the same MTC is followed. Therefore it is important to know which signal goes to which sign in the subtraction block. In short, it acts like some sort of cumulative memory, and it ensures that the error tends to zero as time passes. This is compulsory so as to get the control variable to the desired value.

4.8 Total flow and temperature control system with electronic valves simulation

The proposed system in 3.4 is implemented by adding temperature sensors, flow sensors and electronic ball valves to the conventional system. There are two electronic ball valves one on each line as shown in Fig 4.8. These electronic ball valves can be used to control the water flow rate from heater and cold tank. The ball valve used is designed by a spherical ball and a round sharp-edged orifice. There are two hydraulic ports A and B that are associated with the valve inlet and outlet respectively, and a physical signal port S that receives the control signal from the controller. The water flow rate through the valve is proportional to the orifice opening and to the pressure differential across the valve. The two ball valves receive signals from the Mixer Temperature Controller (MTC) and based on that the required amount of water is released.

The system uses Mixer Temperature Controller (MTC) to adapt the flows adequately, in order to output water at a stable temperature. The system controls the flow ratio between the hot water and the cold water, by means of valves. The inputs require are hot water temperature, the cold water flow rate, the hot water flow rate and the total flow rate from the proximity sensors. With those, two outputs are computed, the valve control signals, and the instantaneous temperature of the mix. There are three cases that should be taken into account: when there is no flow demand, at which point the flows should be zero. Also, when the hot tank temperature is below the mixing temperature, at which point we only

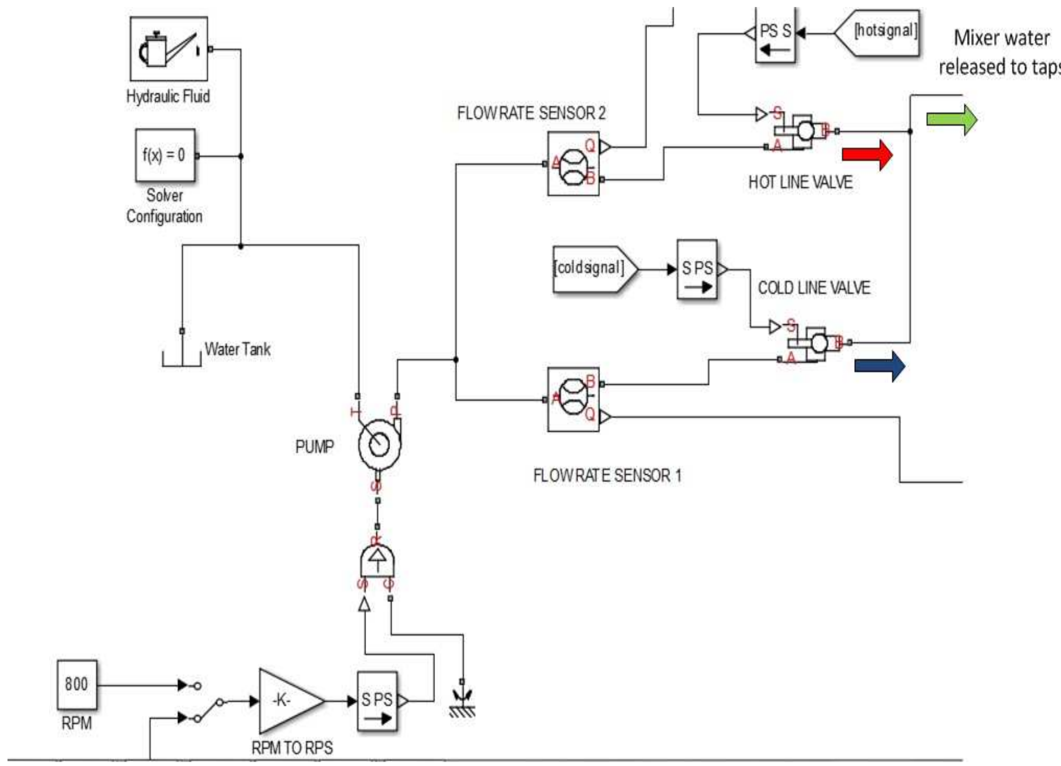

Figure 4.8: TFTCS with electronic valves

want to serve from the hot tank. And otherwise, the flows are computed using the formula we came up with, and used previously. Note that, and this is very important, the q_{total} variable is actually the value from the $q_{totalref}$ signal, as can be seen in the signal routing in the subsystem. This ensures that the sum of the flows will be the desired total flow in every case. There are two simple control loops using a PID controller. As usual, the reference or target value is compared (subtraction) to the actual value, both for the hot and cold flows, and the result is fed into the PIDs. Then the signals are sent to the valve control ports by means of the Goto blocks. The system will keep working properly, as long as the valve orifices remain sufficient to control the system. In other words, if the controller needs to open the valves more than they are able to, the system will malfunction.

The controller used is a PID with fast over damped response. The inputs to the MTC are providing from temperature sensors and the proximity sensors installed. The flow meters installed on hot and cold line provide hot and cold flow rate respectively. The temperature of water in heater and mixer are obtained from the designed temperature models. In this system the hot and cold flow rates are controlled based on the sensor readings. The desired T_{mix} in our simulation is 35 degrees Celsius. The system has a stop switch that is triggered once temperature of water in heater goes below desired T_{mix}, since at that point the controller is unable to operate as expected. From that moment, only water from the heater is served, regardless of the temperature.

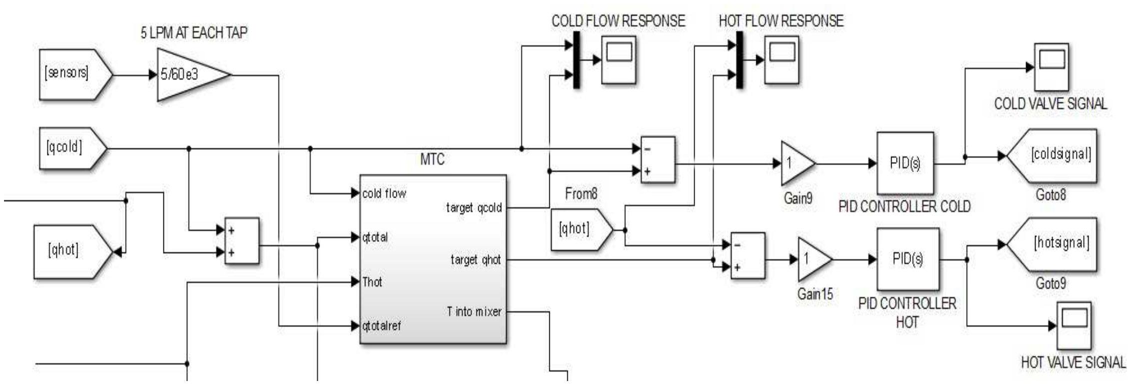

Figure 4.9: TFTCS with electronic valves control model

4.9 Temperature control system with electronic valve

The Temperature Control System (TCS) model is defined as low cost version of TFTCS with electronic valves. In this model there is only one electronic valve and one temperature sensor after the mixer as shown in Fig. 4.10 and 4.11. The pump used is a centrifugal pump that pumps water to generate an average flow rate of 5 lpm at the taps, finding this speed is experimental and it is totally based on the pipe resistances, tap orifice openings and elevation. A fixed orifice block is placed on the cold line which acts as a gate valve that can be operated manually. The function of the fixed orifice is to decrease the pressure of the water on the cold line so that the electronic valve on the hot line can work efficiently. The electronic valve on the hot line works based on the temperature sensor readings mounted after the mixer. The temperature at mixer is calculated using the law of energy conservation. These readings are sent to the MTC that will generate the valve opening correction using the PI controller with fixed gain. The data is communicated using GOTO and FROM tags. In this model there are no proximity sensors and solenoid valves to avoid the water wastage.

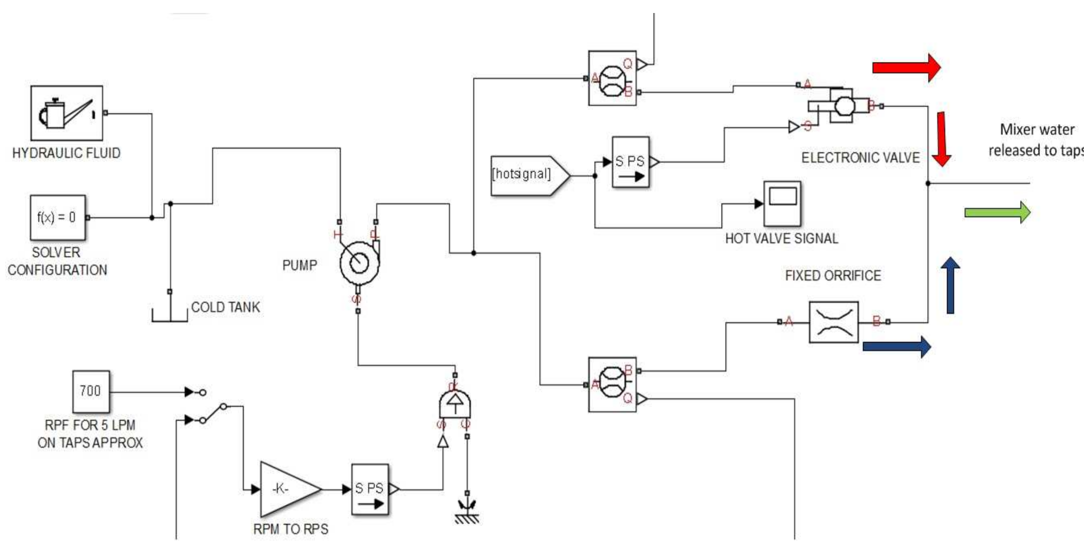

Figure 4.10: TCS with electronic valve

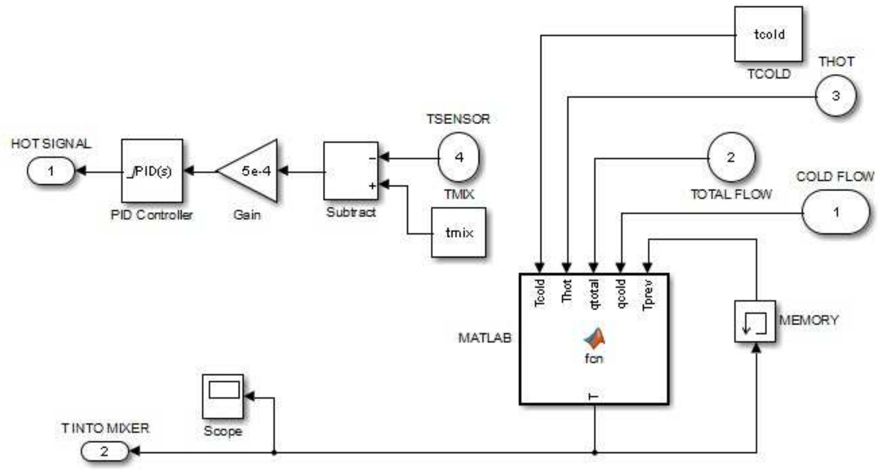

Figure 4.11: TCS with electronic valve control

4.10 PID controller

A PID block internally has three parts. The proportional part multiplies the input signal by an amount. The integral part integrates the input over time, and then multiplies by the provided gain. The derivative part differentiates the input signal over time. The output of the three parts is then summed up and sent to the block output. In our model only PI has been used. Effectively, the integral part increases the output signal when the difference between the actual value and the desired value of the control variable is positive, decreases when its negative, and is zero otherwise. Therefore it is important to know which signal goes to which sign in the subtraction block. In short, it acts like some sort of cumulative memory, and it ensures that the error tends to zero as time passes. This is compulsory so as to get the control variable to the desired value.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Description of ideal system

An ideal system provides:

1. The demanded flow rate to each user.

2. Stablize temperature vs time.

3. Delay the yield point.

In this thesis we designed systems that approaches this idealized system. Simulation results obtained from the four systems will be discussed in this chapter. The systems were simulated for a period of three hours and the behavior of the systems is captured using scope block of Simulink.

5.2 Fixed-ratio system

5.2.1 User Arrivals

The user arrivals are simulated in such a way that it should represent real world scenario. The users arrive randomly at each tap and use it for random service time independent of other taps similar to the users in public places such as airports, railway stations and restaurants, etc. In the simulation model five taps with identical parameters have been used, and the figures from figure 5.1 to figure 5.2 represent the user arrivals at each tap respectively. The value zero indicates that the tap is idle with no user and one indicates that the user has arrived and using the tap. The user arrivals are less in the first hour and exponentially increase in the second and third hour, it shows the behavior of mornings where users are less in the early hours but as the day progresses the user arrivals increase.

5.2.2 Temperature of water in heater in fixed-ratio system

In this section we discuss the behavior of temperature of water in heater in Fixed-ratio system. As shown in fig. 5.6 the temperature starts at 70 degrees celsius and gradually decreases as the time progresses, it follows the heater temperature dynamics presented in the previous section.

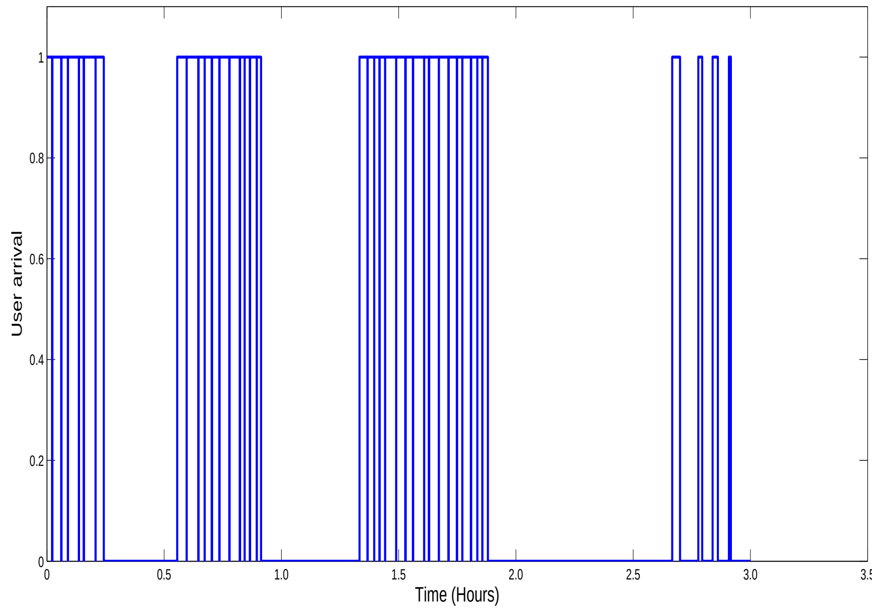

Figure 5.1: Tap 1 user arrival

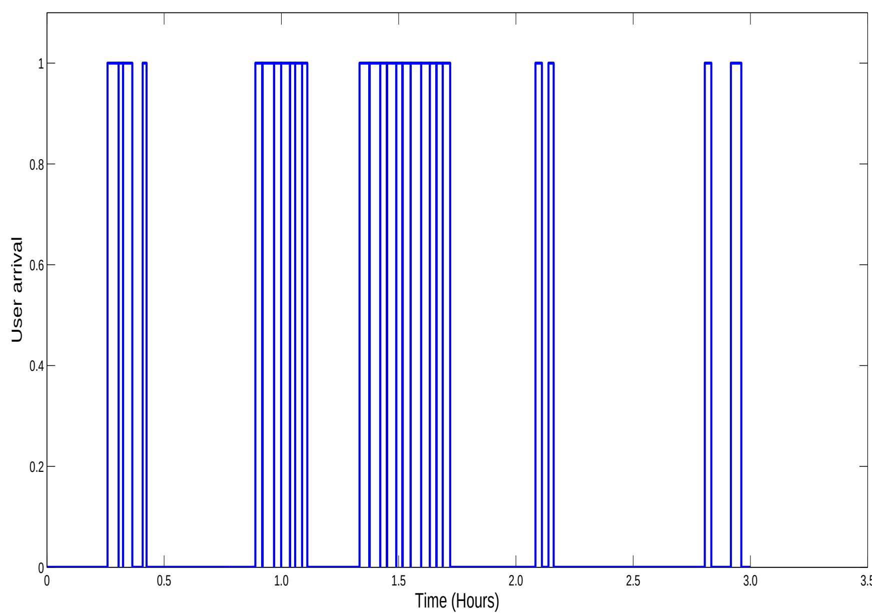

Figure 5.2: Tap 2 user arrival

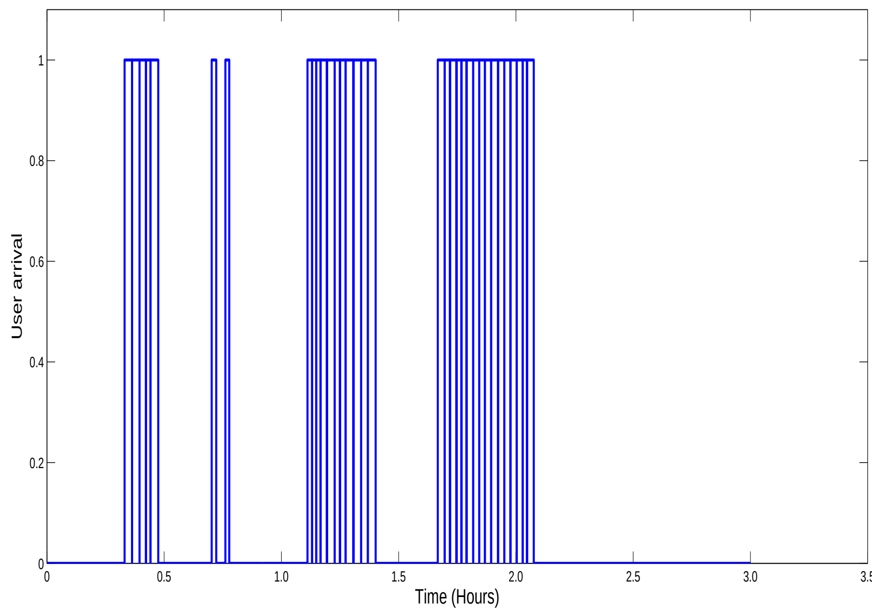

Figure 5.3: Tap 3 user arrival

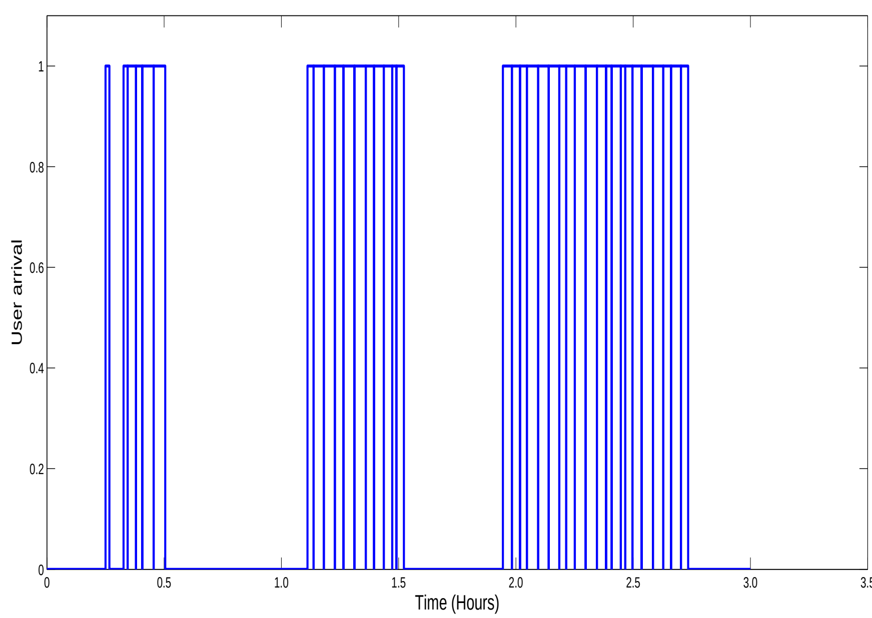

Figure 5.4: Tap 4user arrival

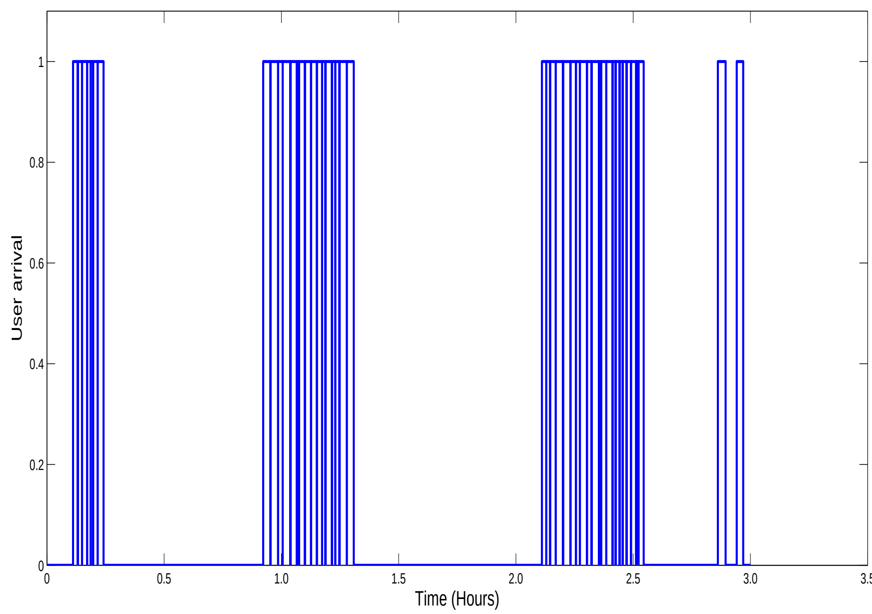

Figure 5.5: Tap 5 user arrival

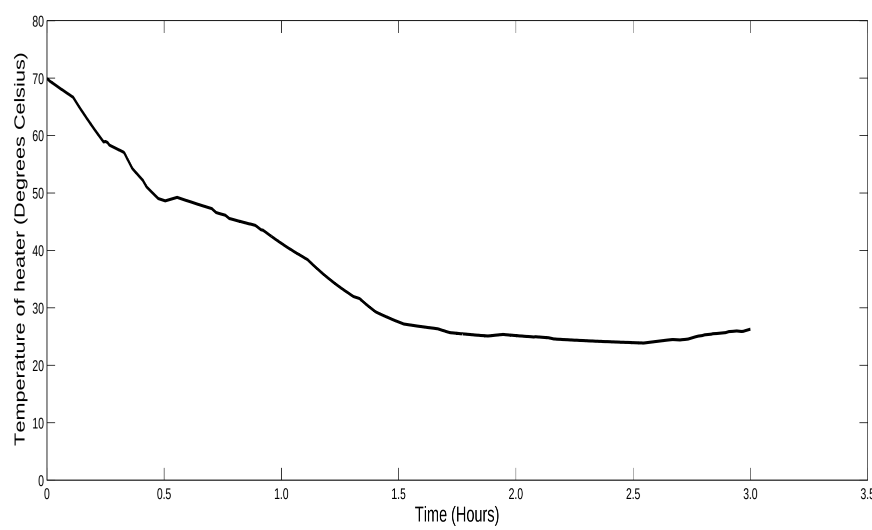

Figure 5.6: Temperature of water in heater for Fixed-ratio System

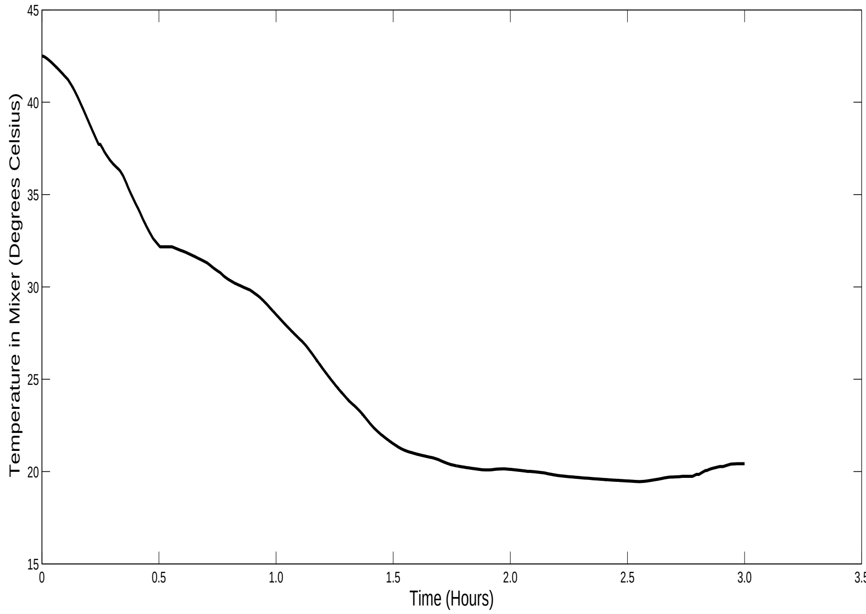

Figure 5.7: Temperature of water in Mixer for Fixed-ratio System

5.2.3 Temperature of water in mixer in fixed-ratio system

In this section we discuss the behavior of temperature of water in mixer in Fixed-ratio system. It is a simple system with no control system to control the mixing of hot and cold water in the mixer. The mixing is done with the ratio obtained by adjusting the valves manually by the users installed on the hot and cold pipes. In our case, we fixed the mixing ratio as 50-50. The graph as shown in figure 5.7 shows that the system serves water at inconvinient temperature (either too hot or too cold) to the users.

5.3 TFTCS user arrivals

The user arrivals and the service time in TFTCS is different from fixed-ratio system. It has user arrivals with only service time where as TFTCS system has user arrivals with service time and also ON and OFF times. Figure 5.8 to figure 5.12 present the user arrivals at taps in TFTCS systems.

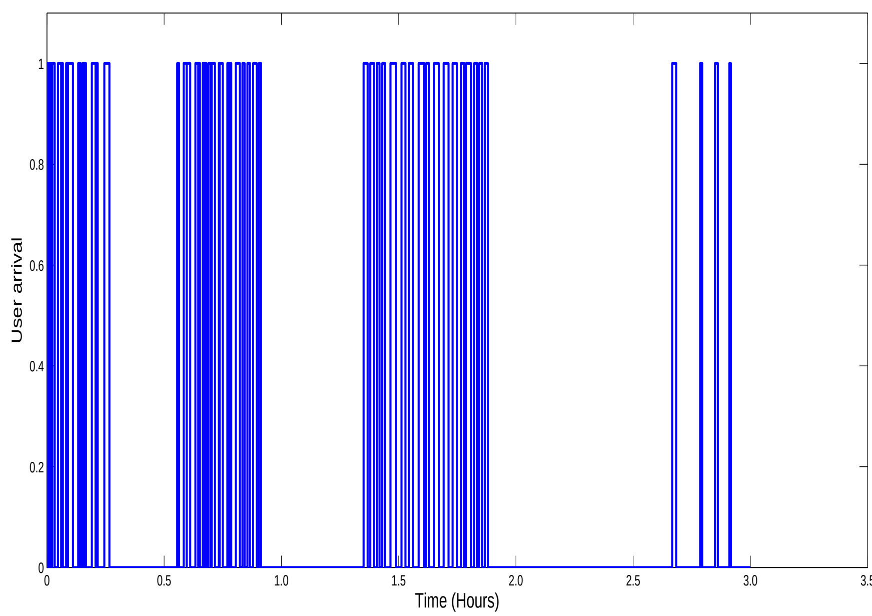

Figure 5.8: Tap 1 user arrival

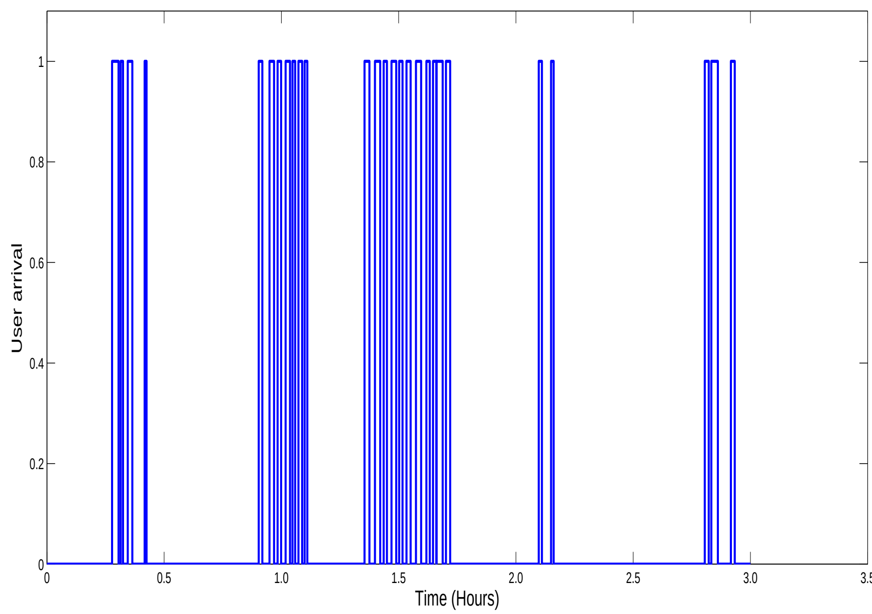

Figure 5.9: Tap 2 user arrival

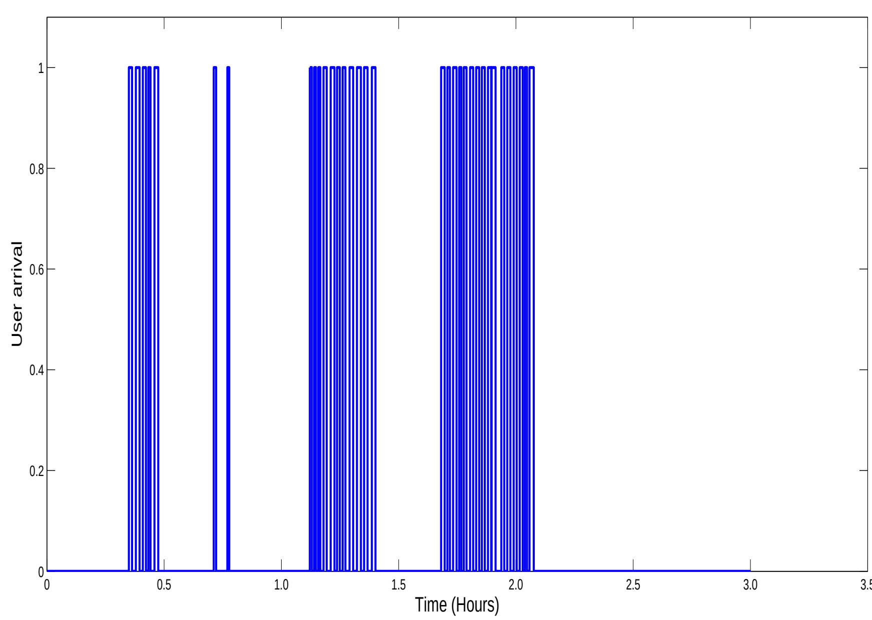

Figure 5.10: Tap 3 user arrival

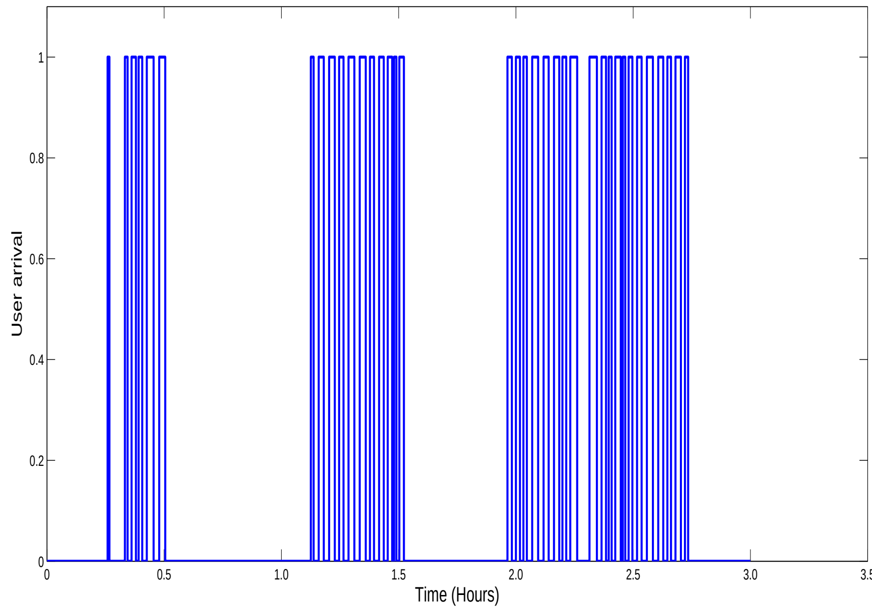

Figure 5.11: Tap 4 user arrival

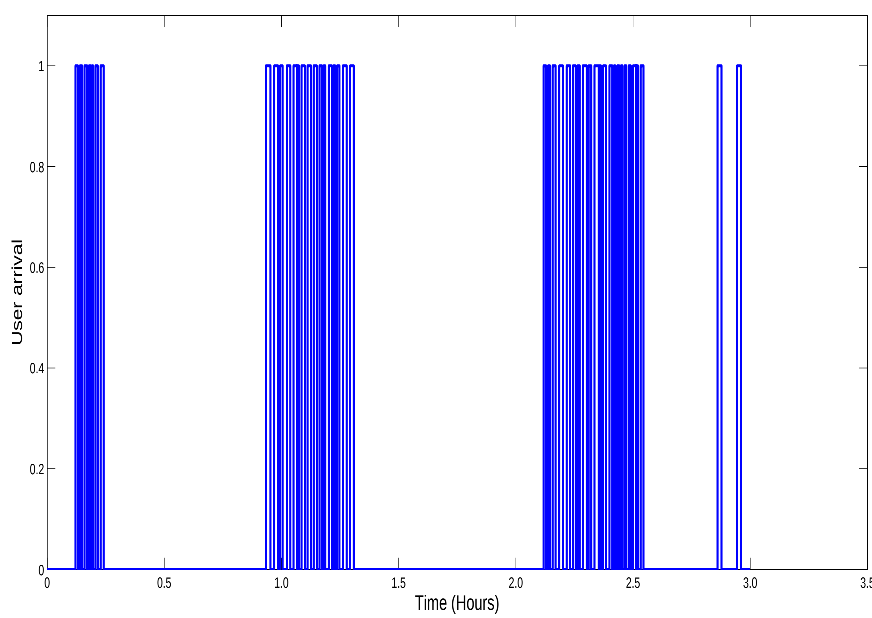

Figure 5.12: Tap 5 user arrival

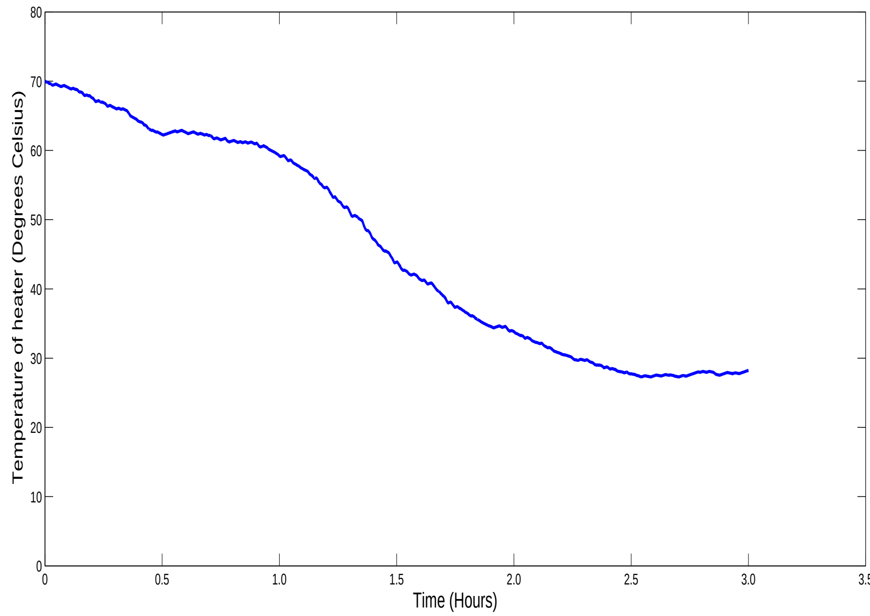

Figure 5.13: Temperature of water in heater in TFTCS with variable speed pumps

5.4 TFTCS with variable speed pumps

5.4.1 Temperature of water in heater in TFTCS with variable speed pumps

The behavior of temperature of water in heater in TFTCS with variable speed pumps as shown in fig. 5.13 is better compared to fixed-ratio system because the physical system is integrated with WSN and control system. The sensors and the controllers installed help TFTCS in using the hot water more efficiently.

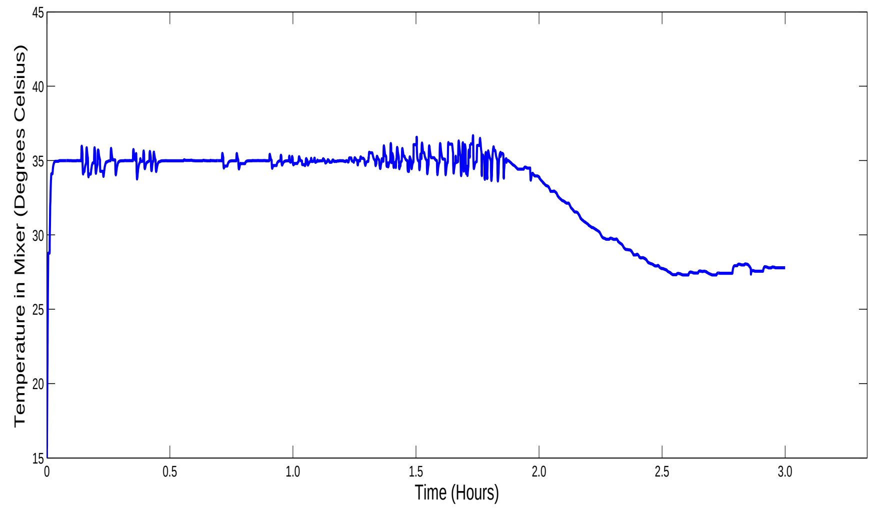

Figure 5.14: Temperature of water in mixer in TFTCS with variable speed pumps

5.4.2 Temperature of water in mixer in TFTCS with variable speed pumps

The graph in the fig. 5.14 shows the behavior of temperature of water served to users in TFTCS with variable speed pumps. The requirement was to deliver water at a temperature of 35 degrees celsius and flow rate of 5 LPM to the users. As the users arrive the system starts pumping water to the users, the controllers designed will help in controlling the mixing as well as flow rates. The temperature of water served fluctuates around 35 degrees during rush hours but the fluctuations are not high.

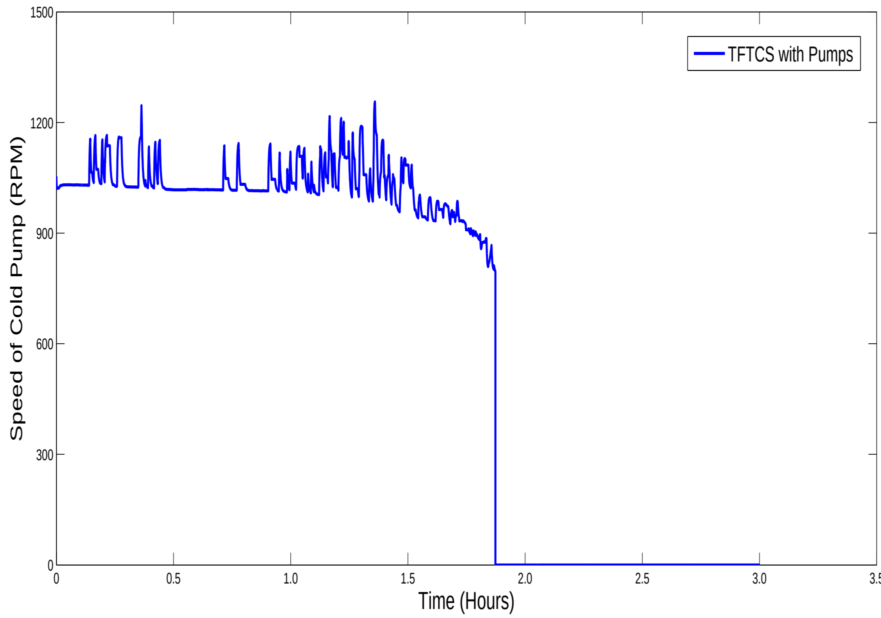

Figure 5.15: Speed of cold pump in TFTCS with variable speed of pumps

5.4.3 Speed of cold pump in TFTCS with variable speed of pumps

In TFTCS we are using two variable speed pumps to pump only that much water that is demanded by the users. The speeds of the pump change in either direction based on the proximity sensor signals and the hot and cold water ratios calculated by the MTC. Fig. 5.15 shows the speed of variable speed pump installed on the cold line. The speed of the pump is varying based on the total flow rate required at users. The rapid fluctuations are due to random user arrivals at the taps. The cold pump is turned off once the temperature of heater falls below the desired temperature.

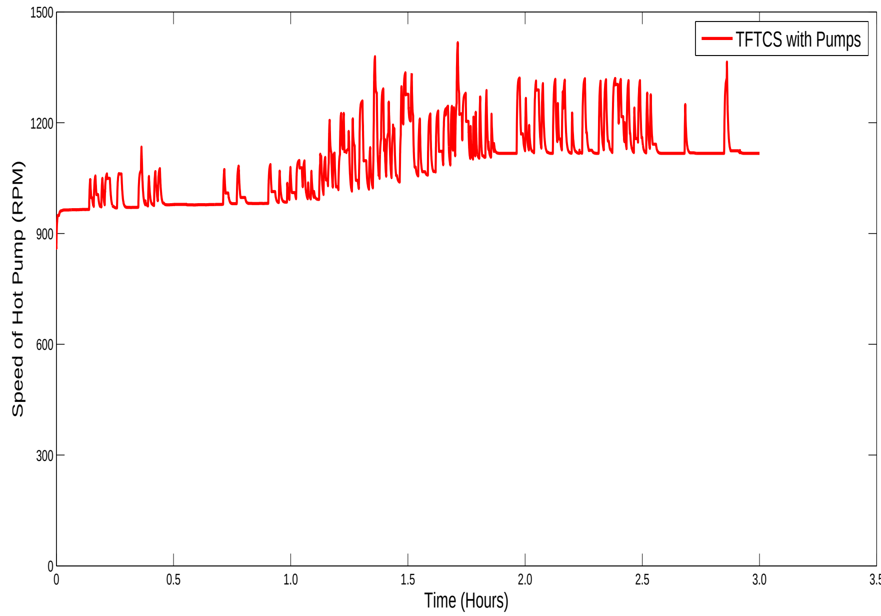

Figure 5.16: Speed of hot pump in TFTCS with variable speed of pumps

5.4.4 Speed of hot pump in TFTCS with variable speed of pumps

Figure 5.16 shows the speed of variable speed pump installed on the hot line. The pump starts once it receives signals from the proximity sensors about the user arrivals at the taps. Initially the speed of the hot pump is low compared to cold pump because the water in the heater is at high temperature. But as the temperature of the water in the heater falls, more water is pumped from the heater, so the speed of the hot pump gradually increases and the speed of the cold pump gradually decreases as shown in the figures 5.15 and 5.16. The cold pump is switched off if $T_H < T_{mix}$, but the hot pump continuous to serve water from heater. The rapid fluctuations in the speed are due to random user arrivals.

5.4.5 Flow rates at Taps in TFTCS with variable speed of pumps

From the daily life observations, it is evident that the flow rates at the public places ranges from 5 to 7 lpm if the tap is fully opened. The flow rates show variation based on the number of taps opened. For example if there are five taps in a restaurant and only one tap is open then it will serve the user with maximum flow rate, but if all the taps are open at the same time then there is a drop in flow rates at each tap. In order to minimize the variations and provide water at constant flow rate and temperature TFTCS was introduced. Figure 5.17 to figure 5.21 shows the simulation results of flow rates at the five taps used in TFTCS with variable speed pumps. The results show that the flow rate at taps is constant during less activity hour and, as the activities increase there are fluctuations in the flow rates. These fluctuations are due to delay introduced by the pump speed adjustment to the changing user arrivals and also the delay introduced during sending the signal from the proximity sensor to the controller and then to the pump.

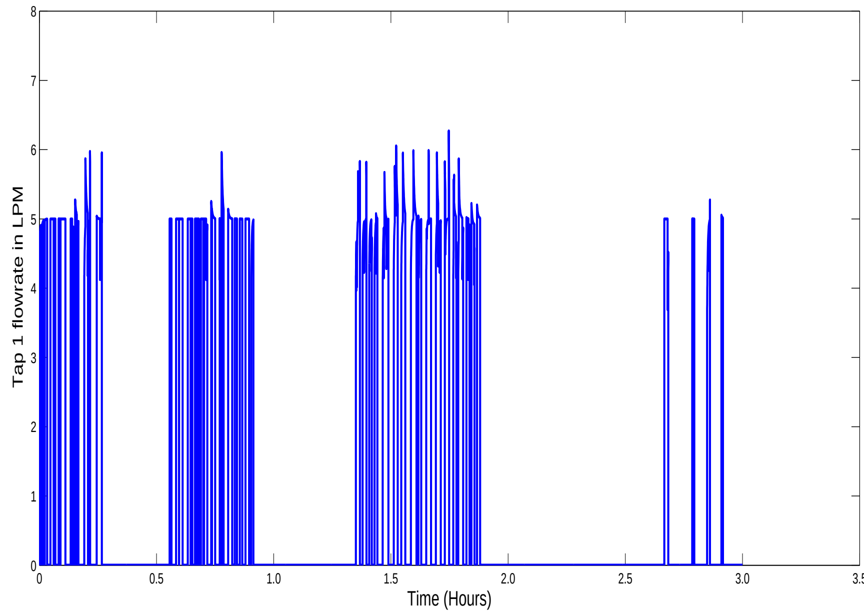

Figure 5.17: Tap 1 flow rate

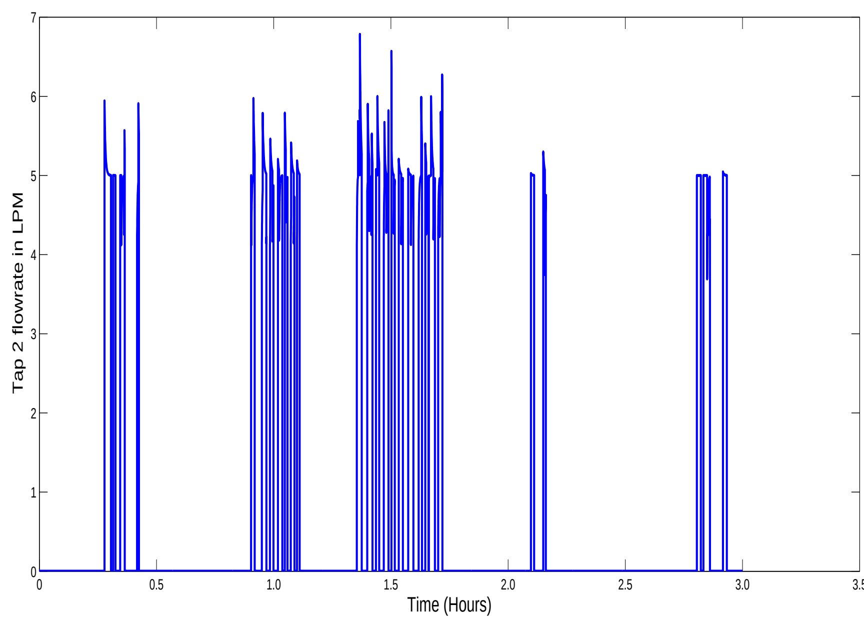

Figure 5.18: Tap 2 flow rate

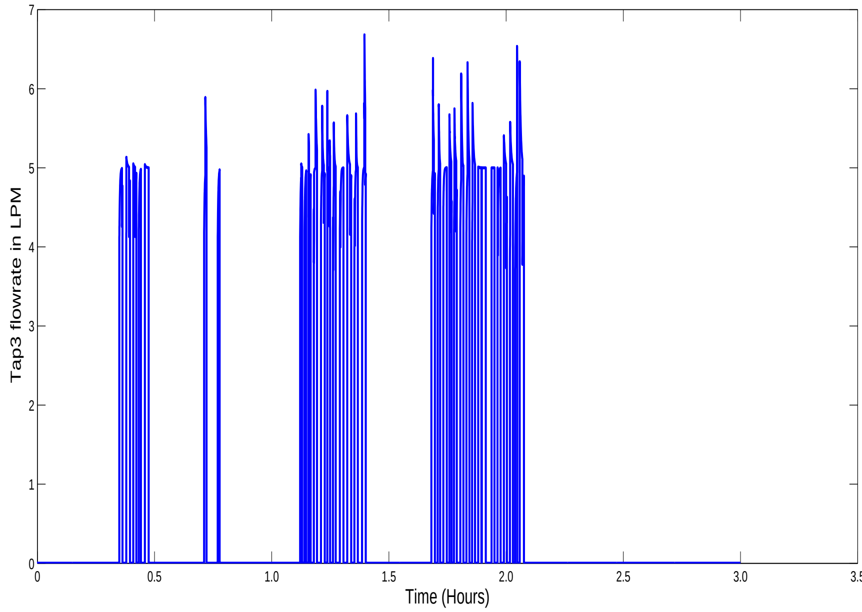

Figure 5.19: Tap 3 flow rate

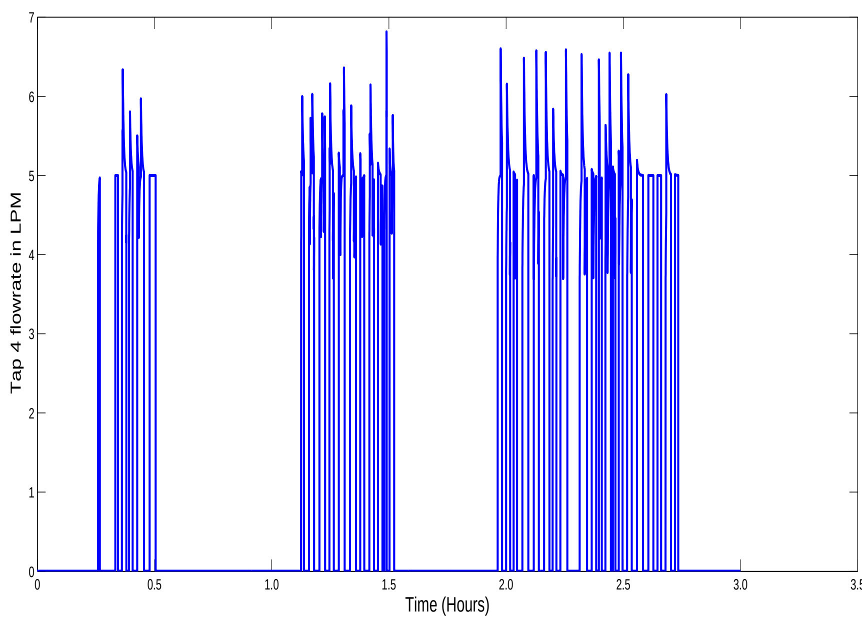

Figure 5.20: Tap 4 flow rate

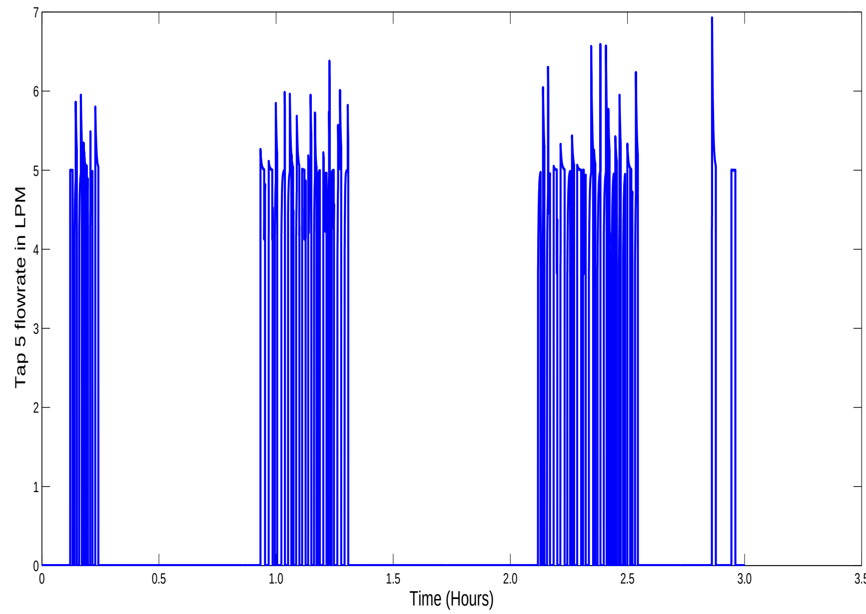

Figure 5.21: Tap 5 flow rate

5.5 TFTCS with electronic valves

5.5.1 Temperature of water in heater in TFTCS with Electronic valves

In this section we discuss about temperature of heater in TFTCS with electronic valves. The Fig. 5.22 shows the heater temperature behavior. The temperature starts at 70 degrees celsius and as the time progresses, the temperature of water is heater decreases exponentially. The behavior is similar to TFTCS with variable speed pumps because we are using the same user arrivals and service times along with ON and OFF times.

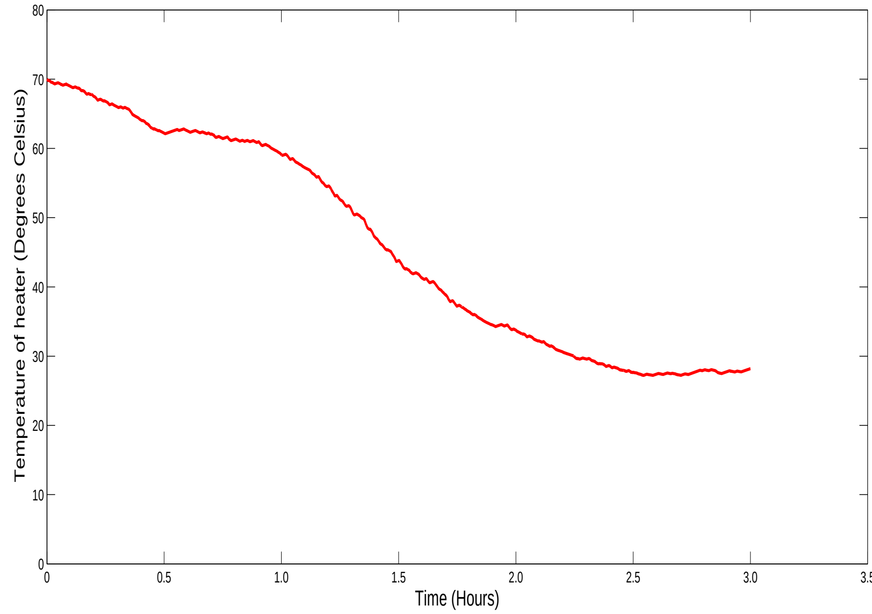

Figure 5.22: Temperature of water in heater for TFTCS with electronic valves

5.5.2 Temperature of water in mixer in TFTCS with Electronic valves

Fig. 5.23 shows the behavior of temperature of water in mixer. It is the temperature at which the water is being served to users at the taps. It is more consistent comapared to the TFTCS with variable speed pumps. The reason is the valves are easily controllable compared to pumps.

5.5.3 Electronic valves in TFTCS with electronic valves

Simulation result in figure 5.24 and figure 5.25 shows the orifice openings of ball valves on cold line and hot line respectively in TFTCS with electronic valves. MTC controls the orifice opening based on the temperature of the water in the heater.

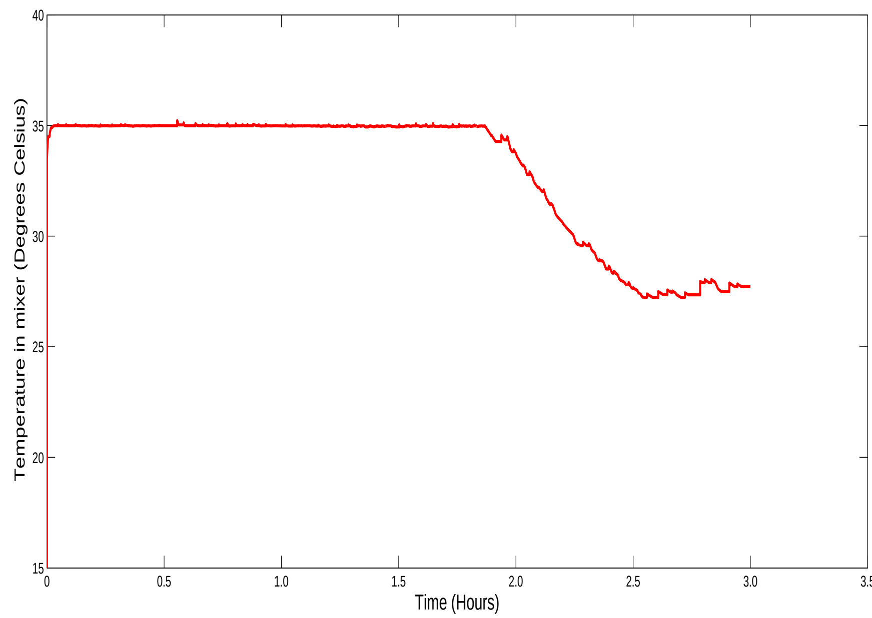

Figure 5.23: Temperature of water in mixer for TFTnCS with Electronic valves

The valve opening is adjusted in order to serve the user with water of desired temperature. In the first hour the water in the heater is at high temperature, so the mixing need less hot water and more cold water that can be seen from the graphs. In the first hour the cold valve has higher value compared to hot ball valve, but as the time progresses and the temperature of water in the heater start decreasing, the cold line valve opening decreases and hot line valve opening increases. After serving for almost an hour, the cold valve readings reaches to zero, it means the temperature of heater has fallen below desired temperature and now the mixer receives water only from heater.

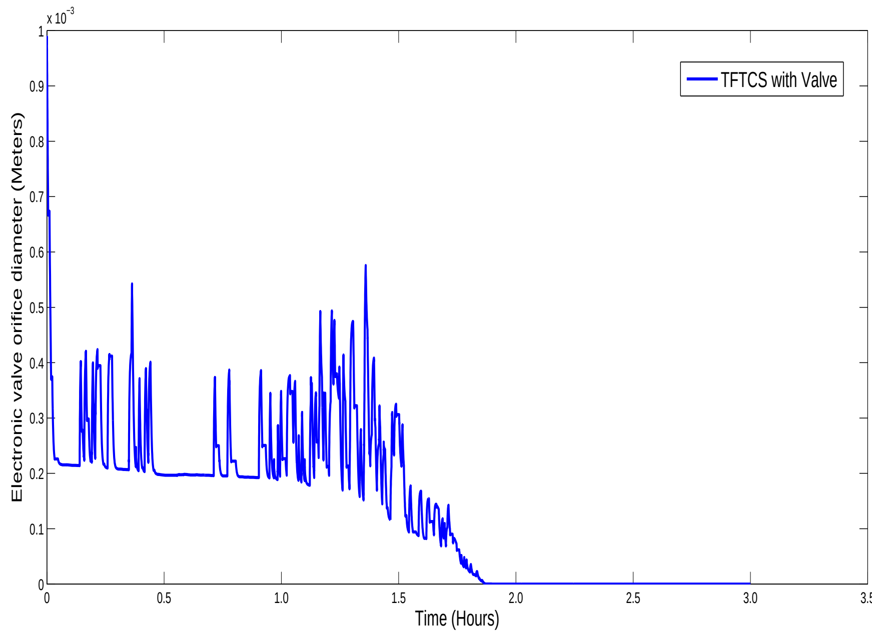

Figure 5.24: Electronic Valve on cold line in TFTCS with Electronic valves

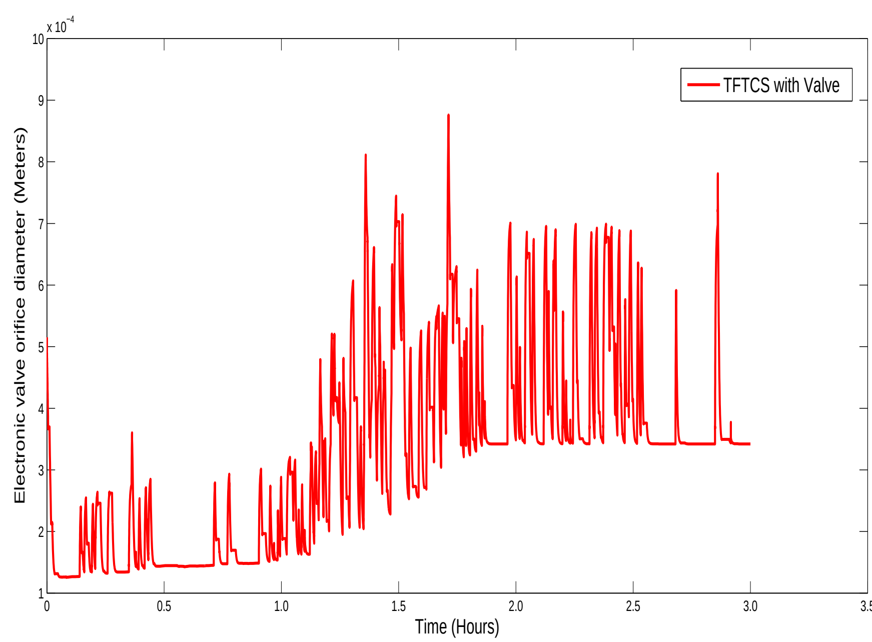

Figure 5.25: Electronic Valve on hot line in TFTCS with Electronice valves

5.5.4 Flowrates at taps in TFTCS with electronic valves

The figures from Fig. 5.26 to 5.30 shows the simulation results of flow rates at the five taps used in TFTCS with electronic valves. The results show that the flow rate at taps is constant during less activity hour and, as the activities increase there are fluctuations in the flow rates. These fluctuations are due to delay introduced by the valve adjustment to the changing user arrivals and also the delay introduced during sending the signal from the proximity sensor to the controller and then to the electronic valve.

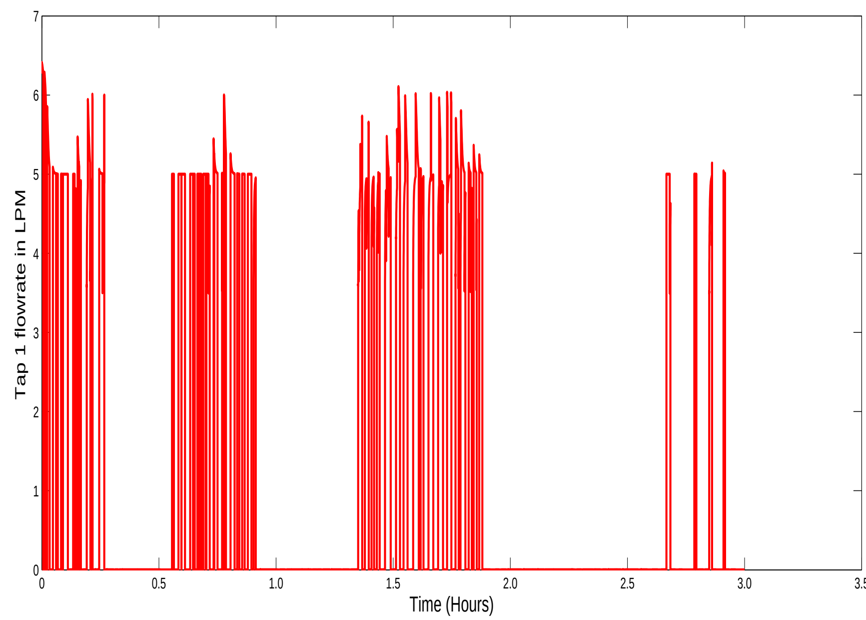

Figure 5.26: Tap 1 flow rate

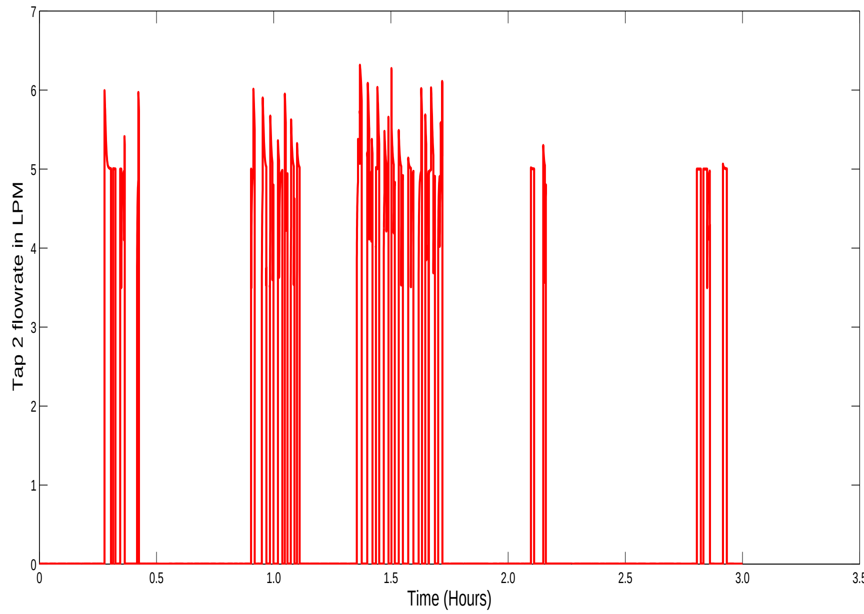

Figure 5.27: Tap 2 flow rate

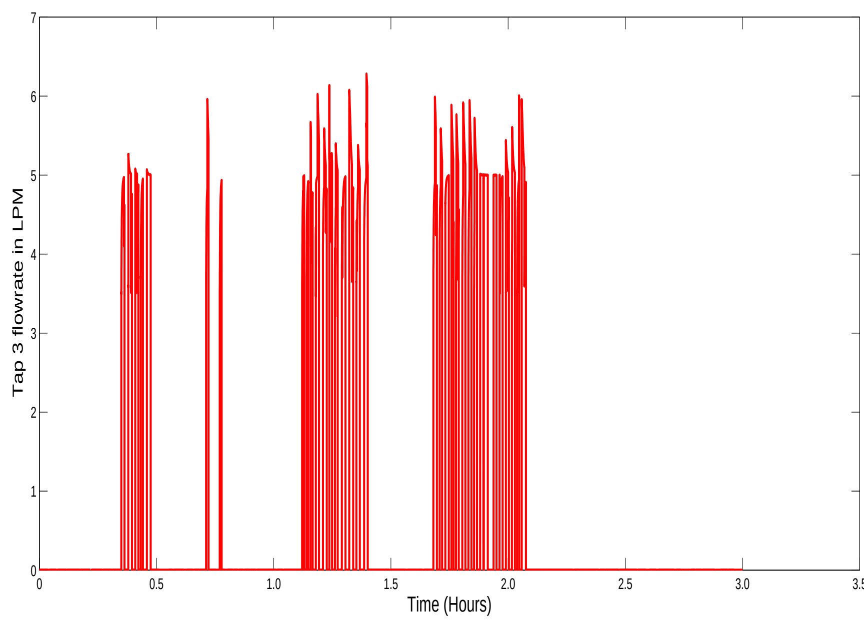

Figure 5.28: Tap 3 flow rate

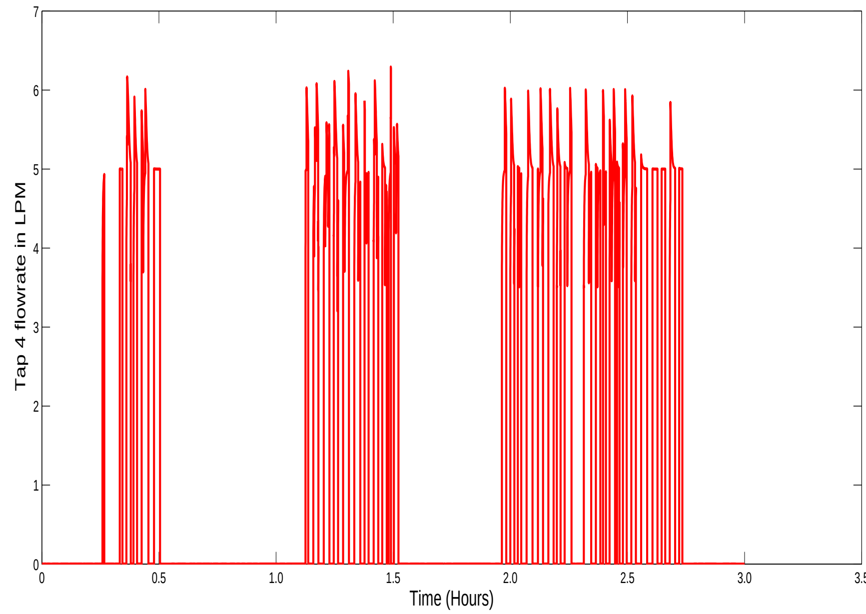

Figure 5.29: Tap 4 flow rate

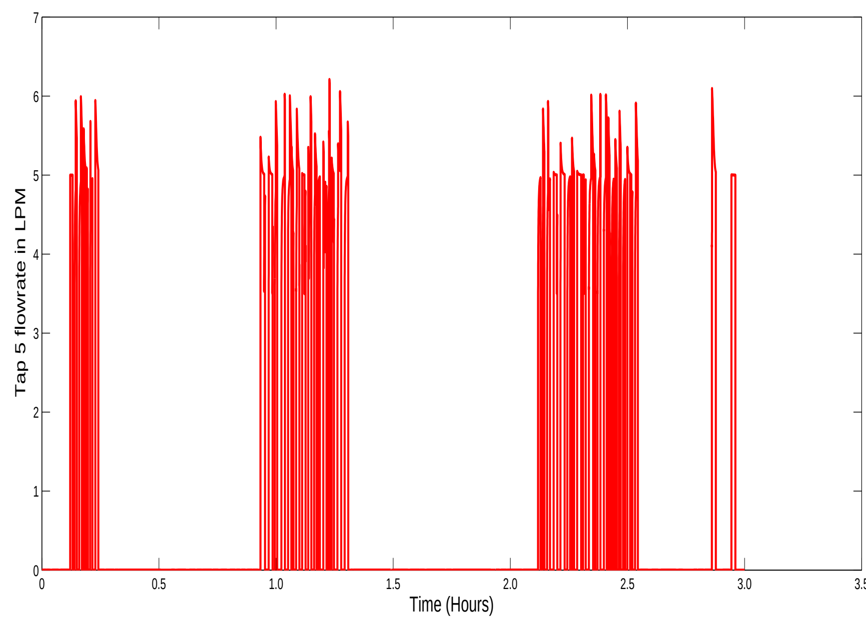

Figure 5.30: Tap 5 flow rate

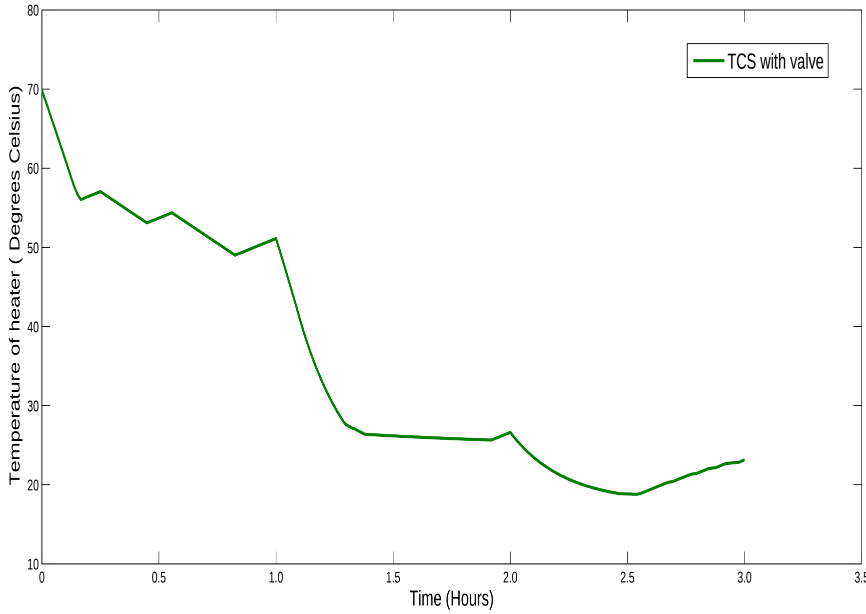

Figure 5.31: Temperature of water in heater for TCS with Electronic valve

5.6 TCS with electronic valve

In this section we will discuss the results obtained after the simulation of TCS with electronic valve.

5.6.1 Temperature of water in heater in TCS with Electronic valve

The performance of this system is better compared to fixed-ratio system but not better than TFTCS because this system has only temperature control system. The fig. 5.31 shows the behavior of the system.

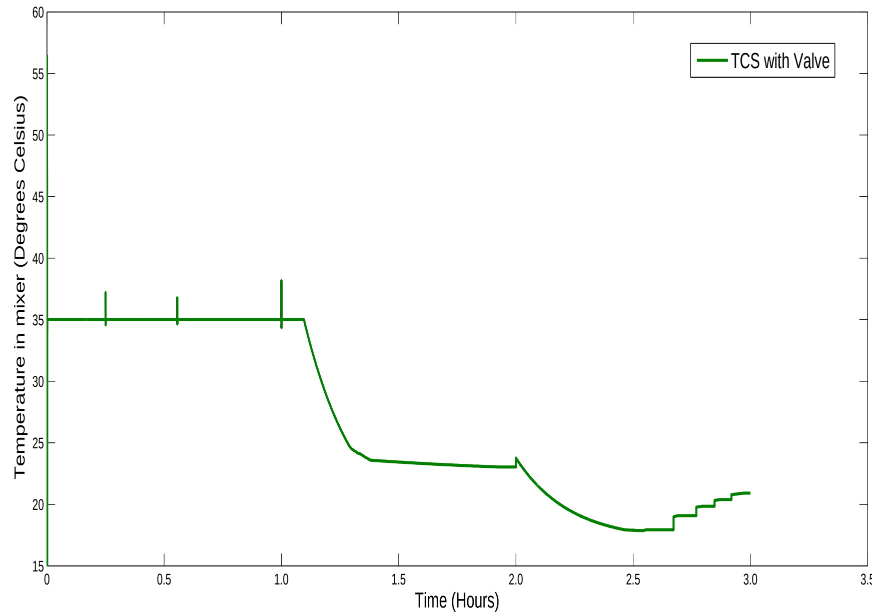

Figure 5.32: Temperature of water in mixer for TCS with Electronic valve

5.6.2 Temperature of water in mixer in TCS with Electronic valve

In this system the controller has no information about the user arrivals, it works based on the temperature of water in the mixer. Everytime the users arrive the system delivers water at high or low temperature for few seconds then based on the readings of the temperature sensor, it controls the flow of hot water in the mixer to get the desired temperature. The spikes in the graph are due to sudden user arrivals after the system being idle.

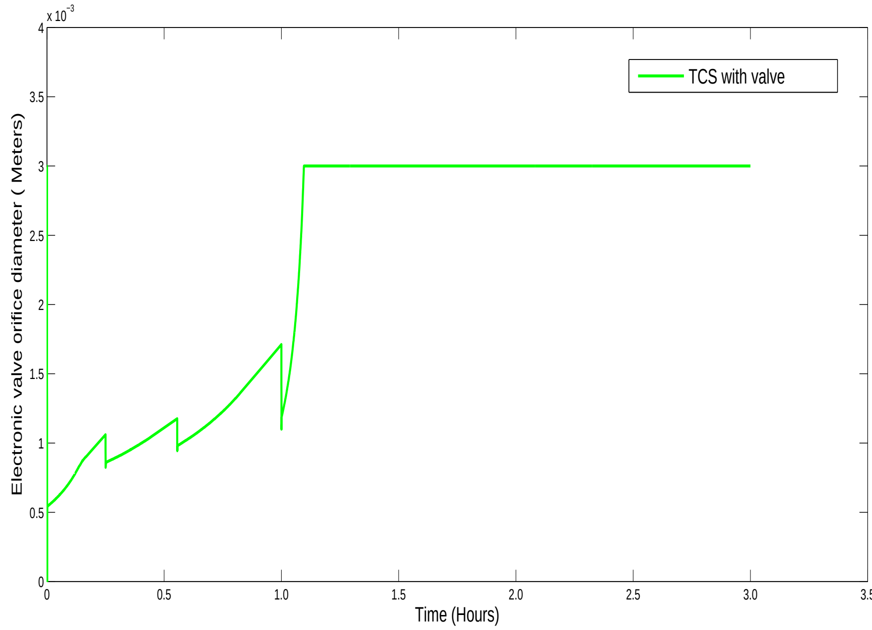

Figure 5.33: Electronic Valve on hot line in TCS with Electronic valve

5.6.3 Electronic valve in TCS with electronic valve

The figure 5.33 shows the behavior of the electronic valve installed on the hot line of the physical system. It starts at some default value at the start of simulation and then adjusts its opening based on the temperature sensor readings. The valve is completely opened when the temperature of water in heater falls below the desired temperature. In such case, the mixer is served with hot water.

5.7 Comparision of four systems

5.7.1 Temperature of water in heater

The temperature in the heater follows the heater temperature dynamics explained in the above section. Fig. 5.34 shows the temperature of water in heater for four

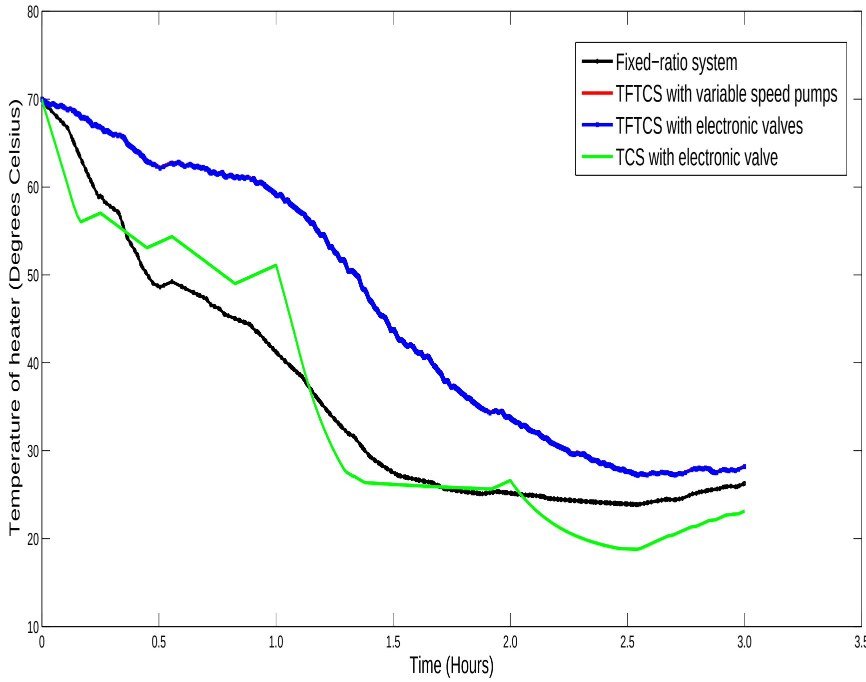

Figure 5.34: Temperature of water in heater

systems. The temperature starts at 70 degree centigrade and gradually drops over the time. The drop in the temperature is more for fixed-ratio system and TCS with electronic valve compared to other two systems because there is no MTC. The two TFTCS system show better performance compared to fixed-ratio and TCS with electronic valve because of proximity sensors and solenoid valves. In TFTCS water is served only during ON times.

5.7.2 Temperature of water in mixer

The temperature in mixer follows the mixer temperature dynamics explained in the above section. Fig. 5.35 shows the temperature of water in the mixer for fixed-ratio and the three CPSs. The fixed-ratio system serves very hot water to

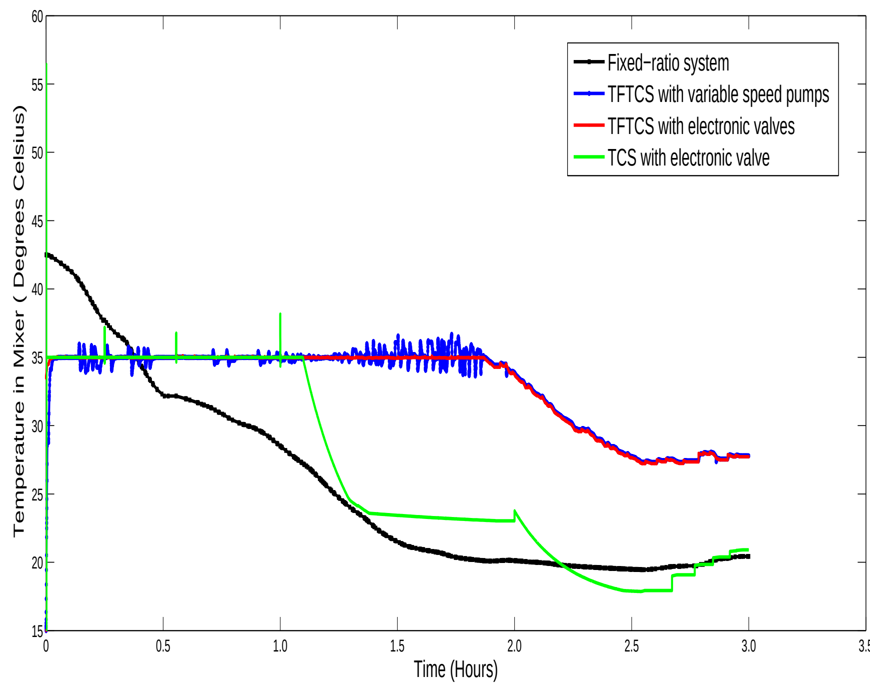

Figure 5.35: Temperature of water in mixer

users arrived in the first hour and gradually drops below the desired temperature in our case it is 35 Degrees Celsius. The performance of two TFTCS systems is better compared to fixed-ratio and TCS with electronic valve because of it smart design in which the water is served to users only in ON times during the service time. The performance of TFTCS with electronic valves is better compared to TFTCS with variable speed pumps because the delay introduced during changing the speed of variable speed pumps is more compared to changing the electronic ball valves openings. The fluctuations are more when there are more user arrivals.

5.7.3 Water conservation in statistics

The main idea behind the implementation of the TFTCS is to save water at the user taps. Fig. 5.37 shows that the two TFTCS has outperformed fixed-ratio and TCS, the reason behind it is the efficient integration of WSN and control system with the present physical system. In fixed-ratio system and TCS, the taps are controlled manually and are open for the whole service time resulting in lot of water consumption. In TFTCS, the taps are open only during ON times. This is achieved using the proximity sensors and solenoid valves at each tap. By avoiding water wastage during OFF times the system saves lot of water. In addition, the total flow is matched to the total number of active users. The table as shown in fig. 5.1 shows the water consumption data obtained from the CPSs.

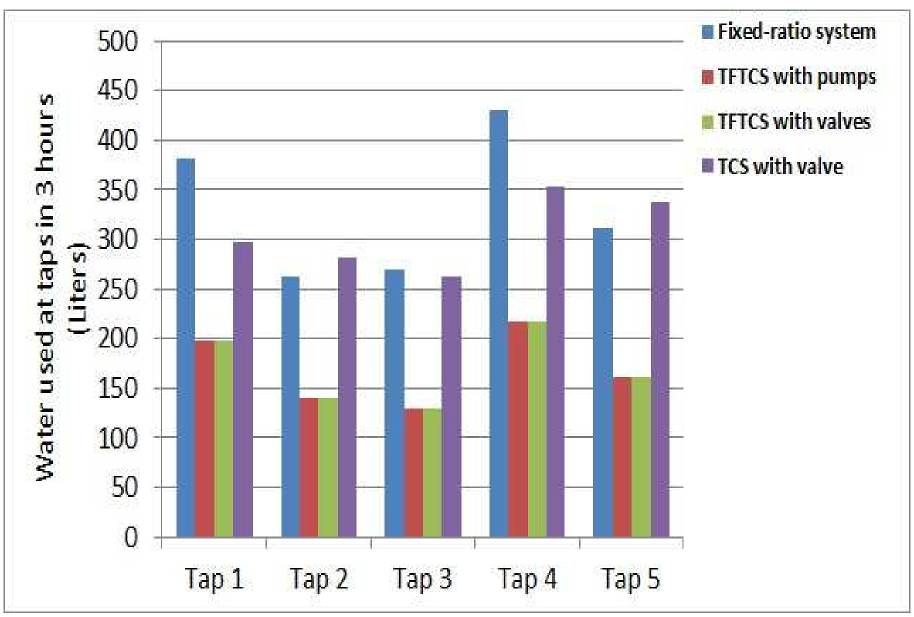

Figure 5.36: Water consumed at taps

Proposed systems	Hot water consumed	Cold water consumed	Total water consumed
Fixed-ratio	827.9	827.9	1655.8
TFTCS with Pumps	593.2	252.5	845.7
TFTCS with Valves	594.8	251.9	846.7
TCS with Valve	1058	473.8	1531.2

Table 5.1: Total water consumed

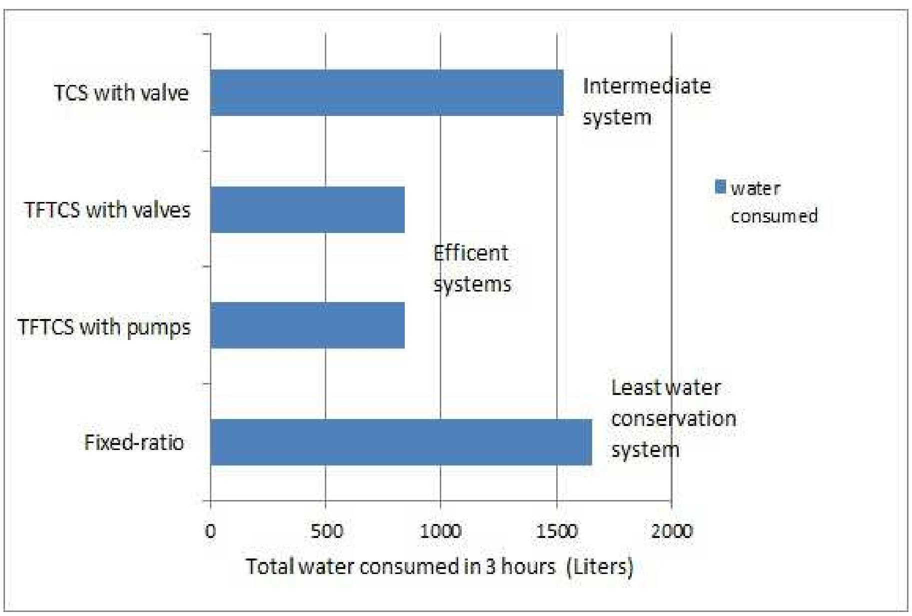

Figure 5.37: Total water consumed

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

In this thesis, we designed simulated and analyzed centralized water mixing systems. The fixed-ratio system with no sensor and a control system provided some comfortable output temperature but generally not adequate to serve the users with desired temperature water and constant flow rate. The proposed smart TFTCS systems and TCS outperform the fixed-ratio system and serve users with thermally stabilized water by reducing wasting due to manual control. TCS can be implemented at low cost and provide stabilized temperature. The results show that automation can significantly reduce water wastage in homes and public places. TFTCS with electronic valves performed more stable than the TFTCS with two variable speed pumps.

In our future work, we will characterize the real world users and implement the newly proposed systems using Arduino boards, sensors, variable frequency drives and valves. The physical system will help confirming simulation results.

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